STATISTICAL ADJUSTMENT OF DYNAMICAL TROPICAL CYCLONE MODEL TRACK PREDICTIONS

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THESIS

STATISTICAL ADJUSTMENT OF DYNAMICAL
TROPICAL CYCLONE MODEL TRACK PREDICTIONS

by

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Statistical Adjustment of Dynamical Tropical Cyclone Model Track Predictions

by

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Captain, United States Air Force
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Submitted in partial fulfillment of the requirements for the degree of

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March 1979

ABSTRACT

A technique of statistically adjusting dynamical forecasts of tropical cyclone motion was tested. All tests were performed with operationally-analyzed data from the U.S. Navy Fleet Numerical Weather Central (FNWC). Three sets of regression equations were developed to modify forecasts of typhoon tracks. The first set of equations was based only on forward integration of the FNWC Tropical Cyclone Model (TCM) for 28 cases in 1975-76. An independent sample of cases from 1977-78 indicated that the first equation set was based on too small a sample size, especially considering the anomalous nature of the 1975-76 storm tracks. A second equation set based only on forward integration of the TCM was derived from 61 storm track forecasts from 1975-78. Results from the experiments with these equations indicate that systematic data and model errors can be used to statistically adjust forecast storm tracks. The second equation set based on forward integration showed improvement over the unmodified model predictions at all forecast times. A third equation set based on forward and backward integration of the TCM explained the greatest amount of variance of all the equation sets. In a dependent test of these equations using 31 of the 1977-78 cases, the U.S. Navy 7th Fleet error goal of 100 and 150 nautical miles at 48 and 72 hours was nearly met.

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LIST OF SYMBOLS

t	Time variable
u	Velocity component in the x-direction
v	Velocity component in the y-direction
x,y	West-east, north-south space axes
θ	Potential temperature
f	Coriolis parameter
u_ψ	Non-divergent component of the wind in the x-direction
v_ψ	Non-divergent component of the wind in the y-direction
g	Acceleration of gravity
M	Map factor
z	Vertical distance above 1000 millibar surface
ϕ	Geopotential height
ϕ_{1000}	Geopotential height of 1000 millibar surface
ω	Vertical velocity in pressure coordinates
P	Pressure (space axis in vertical)
Ψ	Streamfunction
ζ	Vorticity
C_p	Specific heat at constant pressure
Δ	Finite difference operator
R	Gas constant for dry air
ρ	Atmospheric density
∇^2	Laplacian operator
π	Surface pressure
Q	All sources and sinks of heat
$\mathbb{V}$	Two-dimensional vector velocity
W	Variable weighting function
$\overline{F_j}$	Filtered data at point j
F_j	Unfiltered data at point j
α	Smoothing parameter
S	Distance along boundary of forecast domain
V_n	Velocity component normal to grid boundary

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I. INTRODUCTION

The tropical storm is one of nature's most destructive phenomena, making typhoon prediction a major concern worldwide. The need to forecast storm conditions has produced a variety of prediction methods. Subjective methods, including persistence, have generally produced fairly good short-range forecasts. An especially difficult problem for any subjective or objective prognostic scheme is the occurrence of storm recurvature. This problem was significant in the western North Pacific Ocean during the 1975 typhoon season, and to a lesser extent during the 1976 typhoon season. An unusual number of storms tracked northward, while others recurved. As a result, the forecast error statistics were higher than normal (Annual Typhoon Report, 1975). The United States Seventh Fleet Commander, noting the necessity to improve the forecast errors, has levied a requirement for the Joint Typhoon Warning Center (JTWC) to achieve maximum forecast errors of 50, 100 and 150 nautical miles for 24, 48 and 72 hours, respectively. In comparison, the 1977 JTWC average position forecast errors for tropical cyclones at 24-, 48-, and 72-hours were 140, 266 and 390 nautical miles, respectively (Annual Typhoon Report, 1977). The long-term error trend, as indicated by the five-year mean error, has been increasing since 1972. In 1977 the operational TCM produced mean vector errors of 138, 262 and 450 nautical miles for all tropical cyclones (Annual Typhoon Report, 1977).

Although progress has been made in the numerical simulation of tropical storm characteristics such as intensity and spiral bands (Anthes et al, 1974), the major emphasis has focused on storm motion (Hovermale et al, 1976; Ley, 1975). Multi-level, nested-grid models are being developed in an attempt to improve forecast positions over those of analog, persistence and statistical techniques. In spite of the sophistication of some numerical models, undesirable consequences may result from initialization with poor or limited data. One test of the dynamical models is the accuracy of the initial storm track. If the short-term forecasts are inaccurate, a dynamic model cannot be expected to produce accurate, extended forecasts. Some dynamic models (Hovermale et al, 1976; Ley, 1975; Hodur and Burk, 1978) predict tracks with systematic bias relative to the actual track and commonly predict motion which is too slow. A likely source of error seems to be in specification of the initial data fields, although inadequate resolution in the numerical model could also explain the biases.

Since the resources required to increase high quality data or to run sophisticated numerical models are expensive and time consuming, alternative methods for improving model forecasts should be considered. Statistical-dynamical schemes for predicting tropical storm motion (Renard et al, 1972) rely heavily on current storm motion. If position reports of tropical storms are not timely, then the statistical schemes may be impaired. An approach which circumvents many of these problems is to use the model forecast positions

themselves to statistically modify the predicted track positions. It is the primary objective of this thesis to develop and evaluate statistical regression equations for adjusting dynamically predicted storm tracks from the Tropical Cyclone Model (TCM) used by the U.S. Navy Fleet Numerical Weather Central (FNWC).

The basic model used for these experiments is the primitive-equation, three-layer, tropical cyclone model developed by Elsberry and Harrison (1971) and Harrison (1973). Although this model is capable of triply-nested operation (Harrison, 1973), results from Ley and Elsberry (1976) show that the coarse and nested grids produced nearly identical results in a selected case study based on hand-analyzed data. In 1975 FNWC adapted a coarse-mesh (2^{o}), three-layer, dry version of this model for tropical cyclone prediction. Preliminary results with operational data were presented by Hinsman (1977) for 1975 and 1976 data. For the 1977 typhoon season, the model was modified to include a biasing technique suggested by Shewchuk and Elsberry (1978). The use of the forecast stream function field to determine the cyclone forecast positions reduced errors in the relative vorticity tracking used prior to this modification (Shewchuk, 1977). The current operational version of the model has boundary conditions which are insulated, free-slip walls on the north and south and cyclic on the east and west. Since it was suspected that these boundary conditions could adversely affect the forecast storm track, Hodur and Burk (1978) incorporated one-way interactive boundaries. Substantial

improvement in storm track prediction was made compared to the previous channel version of the model. The open boundary version of the TCM was used in the experiments described herein.

II. BACKWARD INTEGRATION

A. THE MODEL

A detailed description of the Tropical Cyclone Model (TCM) is presented in Appendix A. The TCM is a three-layer, primitive-equation model in pressure coordinates. It is an open boundary model with one-way interactive boundary conditions on the north and south and cyclic conditions on the east and west boundaries.

B. MODEL MODIFICATIONS

All forward integration of the model was carried out using the version of the TCM described by Hodur and Burk (1978). The backward integration was carried out using a negative time step of -600 seconds unless the northern boundary location was greater than 40°N. In the latter case, the negative time step was reduced to -450 seconds after the storm moved a sufficient distance to the north.

In the forward integration, heat was added to the storm center as defined by a minimum wind at 1000 mb. The purpose of the heating function is to counteract the dispersion of the vortex due to the finite differencing (Ley and Elsberry, 1976). If heat had been added during the backward integration, this would have contributed to a better definition of the storm center. However, this presents a physically unrealistic situation for a typhoon moving backward in time. For this reason, the heating function was

set equal to zero for all backward integrations. Negative heating was rejected because it led to premature dispersion of the storm, which became difficult to track.

III. APPROACH TO TRACK MODIFICATION

Two types of regression equations were tested here. One type will have predictors based only on forward integration of the TCM, while the other set of predictors will be based on both forward and backward integration of the TCM. The open boundary version of the TCM (Hodur and Burk, 1977; Hodur and Burk, 1978) was run with 46 cases (9 storms) from 1975 and 1976. All cases were based on operationally-analyzed data obtained from FNWC. The regression equations developed from this sample were then tested against independent cases in 1977 and 1978. A second set of regression equations based only on forward integration of the TCM are derived using the combined data sets of 1975-78.

The final set of regression equations are based on forward integration of the model to 72 hours, as well as backward integration for 36 hours. The backward integration should reveal the effects of systematic model and data errors. Fundamental assumptions are that the model-related errors tend to be systematic, and adjustment for data errors is possible where, in the absence of observations, the initial analysis reverts to the east-west flow appropriate to the climatology. Backward integration will increase the number of predictors available to explain the variance between TCM forecasts and best track positions. This should lead to improved regression equations with a higher explained variance. The predictors using backward-integrated positions can be

used to adjust the forward-integrated positions using the same initial data.

Both the forward- and backward-predicted tracks were compared to the best tracks at their corresponding times. Next, regression equations to adjust the predicted track to the actual track using stepwise regression were generated with the Statistical Package for the Social Sciences (SPSS). The regression equations were developed to make corrections every 12 hours up to 72 hours. If a TCM run was incomplete, alternate sets of equations were derived according to the length of the TCM run. The options considered were 36-, 48-, 60-, and 72-hour TCM runs, with and without backward integration.

If successful, the advantage of this approach would be that use of simple regression equations would require much less computer time than more sophisticated dynamic models. Thus, it may be possible to produce tracks that are more accurate than the ordinary open boundary TCM without a large increase in computer resources. An operational advantage of this approach is that no warning positions are required for computation of any predictors in the regression equations. The method and results of this approach to storm track prediction are presented in the following sections.

IV. DEVELOPMENT OF THE REGRESSION EQUATIONS

A. THE PREDICTORS AND PREDICTANDS

Using TCM forecast runs versus best tracks (Annual Typhoon Reports, 1975-77), 12 predictands were derived by computing the east-west and north-south differences between positions at corresponding times (see Fig. 1). Storm positions at each forecast time are adjusted by two regression equations, one for the east-west direction and the other for the north-south direction. Thus, for a 72-hour TCM forecast run, a total of 12 regression equations would be used to modify storm tracks in 12-hour increments from 12 to 72 hours.

Predictors used in these equations were model-predicted displacement and velocity, broken into components along the east-west and north-south directions. The Julian day, latitude and longitude of the initial position of each TCM forecast run are also included as predictors in the regression equations. A schematic illustration of the intervals over which the predictors were calculated for the forward integration runs is shown in Fig. 2. A complete list of predictands and predictors, with the times for which they were computed, appears in Table I.

B. METHOD OF EQUATION DERIVATION

The regression equations were derived using the Statistical Package for the Social Sciences (Nie, et al, 1975). Cases with missing values for predictors or predictands were

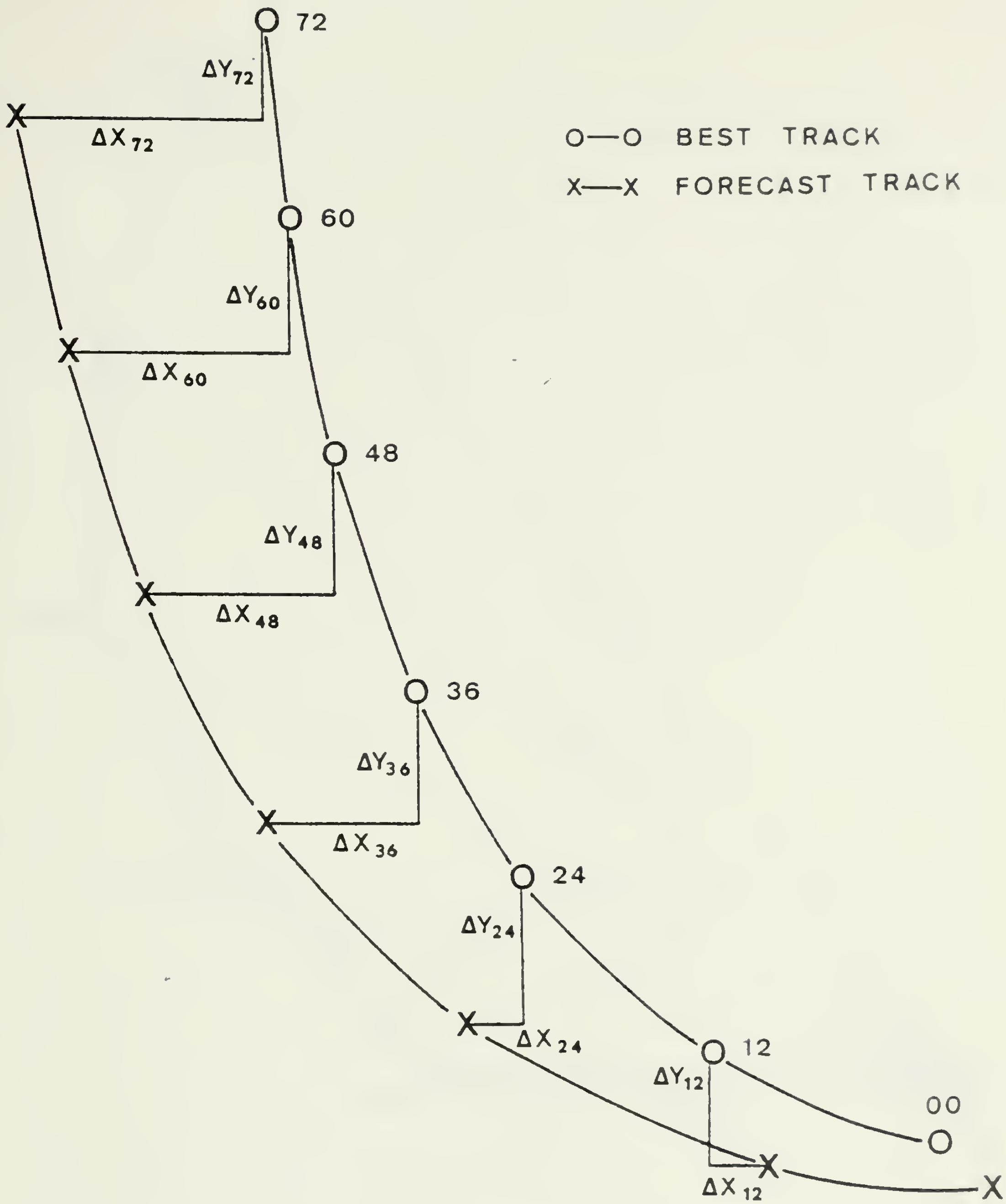


Figure 1. Depiction of the model errors (i.e., the predictands), which are the difference between the best track and forecast positions, which are shown above as ΔX_{12}, ΔY_{12}, ΔX_{24}, ΔY_{24}, etc.

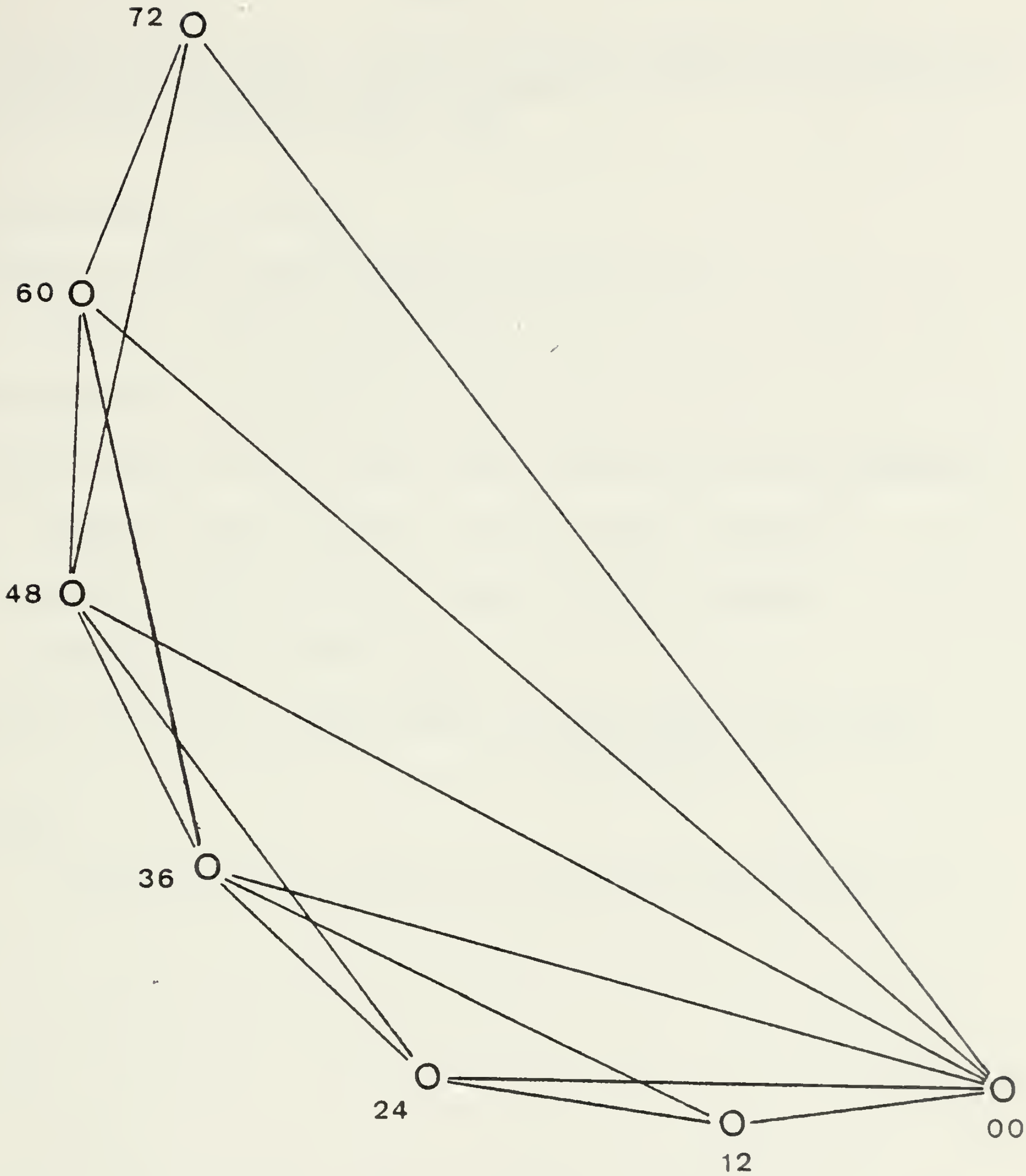


Figure 2. Depiction of intervals over which displacements and average speeds were computed using only forward integration of the open boundary TCM. Unmodified TCM forecast positions (O) are shown at 12 hour intervals.

TABLE I

Predictors/predictands used to develop regression equations for typhoon track modification based only on forward integration of the open boundary TCM.

1. Predictands: ΔX, ΔY

   Times at which predictands are computed:

   12, 13, 26, 38, 60, 72 hrs

2. Predictors: ΔX, ΔY, u, v

   Time intervals over which each predictor was computed:

   00-12, 12-24, 24-36, 36-48, 48-60, 60-72,

   00-24, 12-36, 24-48, 36-60, 48-72, 00-36,

   00-48, 00-60, 00-72 hrs

3. Initial Position Predictors: Julian Day, Latitude, Longitude

   Times:

   Initialization time of a given TCM forecast run

automatically eliminated from all calculations. Such cases arise because the tracking routine is not always able to follow the storm center throughout the 72-hour interval. In the forward integration tests of Hodur and Burk (1978) with the open-boundary conditions, only 28 of the 46 cases extended to 72 hours.

To avoid the problem of uncomputable predictors when the duration of TCM runs was less than 72 hours, it was decided to derive alternate sets of equations based on the duration of the TCM forecast run. The forecast lengths considered were 36, 48, 60 and 72 hours. For example, if the TCM produced only a 48-hour storm track forecast, no regression adjusted track would extend behond 48 hours, and only predictors in the range 00-48 hours were considered when deriving the regression equations to be applied to a 48-hour TCM run.

All predictors listed in Table I were considered for inclusion in each regression equation. Selection of predictors was stopped when the next variable in the stepwise regression explained less than 1% of the variance.

C. FIRST EQUATION SET BASED ON FORWARD INTEGRATION

The 1975-76 cases, as well as those in 1977 and 1978 to be discussed later, are based on cases with relatively well-developed storms which are more readily modeled by the coarse-mesh TCM. It should be noted that the operational version of the TCM is used only for storms exceeding 50 knots. Inclusion of weaker tropical storms would likely increase the variance

between the forecast and best track positions, thus making it more difficult to derive stable regression equations. A sample equation for the regression adjustment along the x-axis at 72 hours is shown below:

$$\begin{aligned} DXER72 = & -537.0151 + 39.2088(XXLAT) + 68.1605(VX1224) \\ & - 50.1251(VX0024) - 43.8154(VY0048) \\ & - 1.4956(DX6072) + 0.6102(JULDAY) \end{aligned}$$

Velocity was the most frequently selected predictor. This result is not too surprising if one recalls that a common fault of dynamic models is prediction of motion which is too slow (Hovermale et al, 1976; Ley and Elsberry, 1976). The version of the TCM (Hodur and Burk, 1978) used in these experiments is no exception. Predictors with their associated time intervals beginning, ending or overlapping the valid time of a given regression equation were often selected. In general, this suggests a sort of "statistical extrapolation" in which past, present and future forecast motions are used to correct the forecast track.

The average explained variance of the regression equations appears in Table II. This parameter measures the strength of the linear relationship between the multi-linear regression equation value and the observed value. The amount of explained variance in Table II generally decreases as the TCM runs become shorter in duration and the number of available predictors is thereby reduced. In general, longer TCM forecast runs permitted use of regression equations which corrected for more of the variance from the best track.

TABLE II

Average explained variance of the regression equations.

Forward Integration (1975-76 Cases)

72 Hr TCM Run	81.6%
60 Hr TCM Run	77.6%
48 Hr TCM Run	75.4%
36 Hr TCM Run	68.4%

Forward Integration (1975-78 Cases)

72 Hr TCM Run	51.5%
60 Hr TCM Run	46.5%
48 Hr TCM Run	47.6%
36 Hr TCM Run	43.2%

Forward and Backward Integration (1977-78 Cases)

72 Hr TCM Run	86.2%
60 Hr TCM Run	84.3%
48 Hr TCM Run	83.8%
36 Hr TCM Run	82.8%

Shortcomings (see Fig. 3) of the one-way (OW) interactive boundary version of the TCM are that the forecast track typically runs to the left of the storm path and the velocities are generally too slow (Hodur and Kurk, 1978). These systematic errors of the TCM seem to contribute significantly to the large amount of explained variance in the regression-produced typhoon positions (see Table II).

It should be recalled that the 1975 typhoon season, and to a lesser extent the 1976 season, experienced a high frequency of storm recurvature as well as a large number of storms which tracked northward. This bias was present in the data sample used to derive the regression equations and had considerable impact on the selection of predictors and the computation of constants and coefficients.

D. SECOND EQUATION SET BASED ON FORWARD INTEGRATION

To increase the number of typhoon cases used to derive the regression equations, TCM forecast runs from 1977 and 1978 were included in the data set. These TCM forecasts were originally used to make an independent test of the 1975-76 regression equations. However, the majority of the typhoons in 1975 and many in 1976 had significant recurvature. The inclusion of the 1977-78 storm tracks should make the sample more representative of the various tracks found in the western North Pacific Ocean area.

Because some TCM runs did not extend to 72 hours, only 61 of 90 cases were available for derivation of the regression equations. As with the first set of equations based

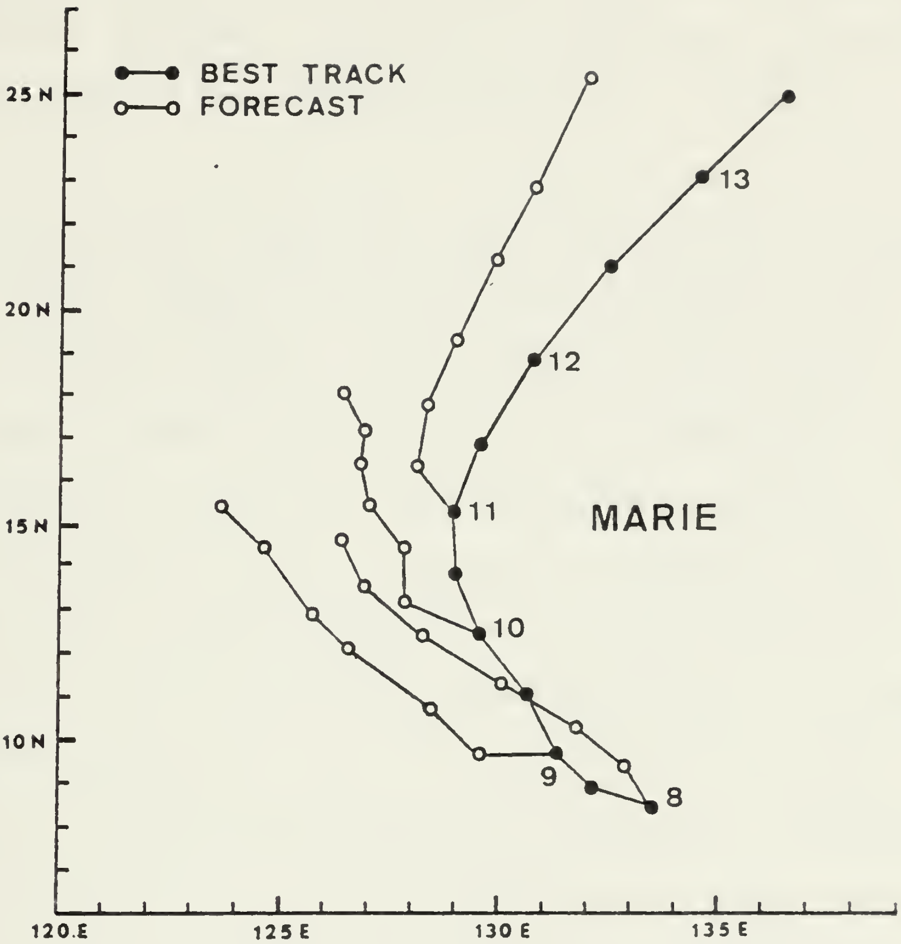


Figure 3. Forecast tracks of Typhoon Marie produced by the OW model compared to the 8-13 April 1976 best track positions. Each circle represents a 12-hour increment (after Hodur and Burk, 1978).

on the forward integration of the TCM, alternate sets of equations were derived based on 72-hour, 60-hour, 48-hour and 36-hour TCM runs. When less than 1% of the variance was explained by a variable, selection of predictors was halted. The complete set of regression equations is listed in Appendix B.

The expanded data sample (61 cases) contained a greater variety of storm tracks and reduced the recurvature bias of the 1975-76 typhoon cases. Storm tracks in the 1975-78 data set used in these experiments are characterized by four general categories: westward, northwestward, northward, and recurving paths. With this greater variety of storm paths, the amount of explained variance of the regression equations (see Table II) dropped commensurately. For example, the regression equations for a 72-hour TCM run incurred approximately a 30 percent decrease in explained variance. With the exception of a small variation at 48 hours in Table II, the general trend was again a reduction of explained variance as the duration of the TCM forecast runs decreased to 36 hours. As discussed previously, this characteristic is attributed to having fewer predictors available to explain the variance when the TCM forecast is of shorter duration. These results reaffirm that this method of adjusting TCM forecasts is at its best when the TCM forecast extends to 72 hours, rather than a shorter forecast interval.

Velocity was again the most frequently selected type of predictor, indicating an attempt to compensate for the overall slowness of the TCM. However, there was a better

balance of velocity and displacement predictors in the 1975-78 equations as compared to the 1975-76 equations.

E. EQUATION SET BASED ON FORWARD AND BACKWARD INTEGRATIONS

The third set of regression equations was based on storm positions derived from both backward and forward integration of the TCM. Additional velocity and displacement predictors based on backwards integration of the TCM as indicated in Fig. 4 and Table III were added to the data set. These predictors are computed in the same manner as those based on forward integration. All predictors listed in Table I and Table III were considered for inclusion in each regression equation. Regression equations were again developed for TCM forecast runs of 36, 48, 60 and 72 hours duration.

The regression equations which included backward-integrated positions had the highest average explained variance (see Table II). As TCM forecast runs become shorter in duration, the amount of explained variance in the equations decreases due to fewer predictors being available (see Table II). The complete set of regression equations is listed in Appendix B.

The regression equations took advantage of the systematic errors inherent in the initial fields and in the numerical model. The most favored predictors from the backward integration occurred in the interval from -12 to 00 hours. For the 12 equations used when the TCM was integrated forward to 72 hours and backward to -36 hours, predictors in the interval -12 to 00 hours appeared in 9 equations. The

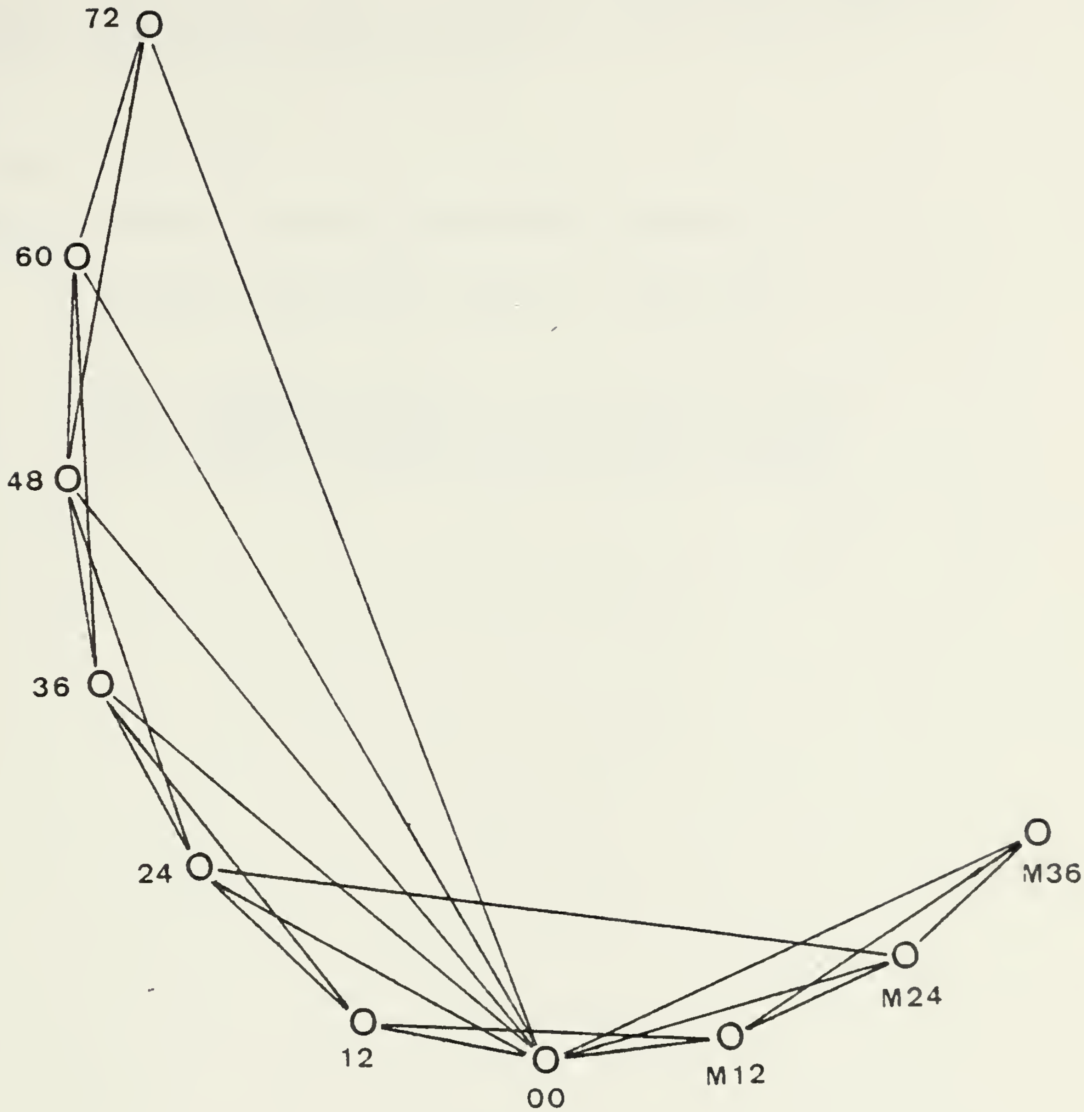


Figure 4. Depiction of intervals over which displacements and average speeds were computed using both forward and backward integration of the open boundary TCM. Unmodified TCM forecast positions (0) are shown at 12-hour intervals.

TABLE III

Additional predictors used to develop regression equations for typhoon track modification based on the backward integration of the open boundary TCM.

Predictors: ΔX, ΔY, u, v

Times = 00-M12, M12-M24, M24-M36, 12-M12,

00-M24, M12-M36, 00-M36, 24-M24 hrs

where 00 = initial time
M24 = minus 24 hours from initial time
12 = plus 12 hours from initial time

velocity along the y-axis from -12 to 00 hours appeared in 7 of the equations, and in each case it explained the most variance of any predictor in the equation. Approximately 35 percent of all the predictors in these 12 regression equations were computed from backward-integrated storm positions. Velocity was the most frequently selected predictor from all forecast intervals. As will be indicated in later examples, the regression equations appeared to be compensating for the generally slow motion of the TCM. It should be noted here that these regression equations and the sample cases which follow were based on a limited data set of 31 storm cases from 1977 and 1978.

V. RESULTS

A. FIRST EQUATION SET BASED ON FORWARD INTEGRATION

The primary purpose of the tests with the 1975-76 cases was to make a preliminary evaluation of the regression equations which were derived using this data set. Because this data set was used to derive the regression equations, these experiments are referred to as a dependent test.

A sample of adjusted storm positions based on the first equation set is shown in Figs. 5-7. Results with Typhoon June shown in Fig. 5 and Typhoon Marie depicted in Fig. 6 were very encouraging. Typhoon Marie is the same storm which appears in Fig. 4. Storm recurvature was accurately depicted, and storm velocity was markedly improved in these two storms. Note, however, that the velocities in the regression tracks are generally greater than the best track velocities. This characteristic of the regression equations appears to be an attempt to compensate for the slowness of the TCM. In the majority of cases in this sample, the storms were excessively accelerated due to this feature of the equations. Since the regression equations were based primarily on predictors derived from TCM forecasts, it is clear that the goodness of the regression-adjusted storm track is dependent on the quality of the TCM forecast itself. The adjusted track for Typhoon Rita (August 1975) shown in Fig. 7 illustrates how a poor TCM forecast will lead to an extremely radical regression adjustment. This example

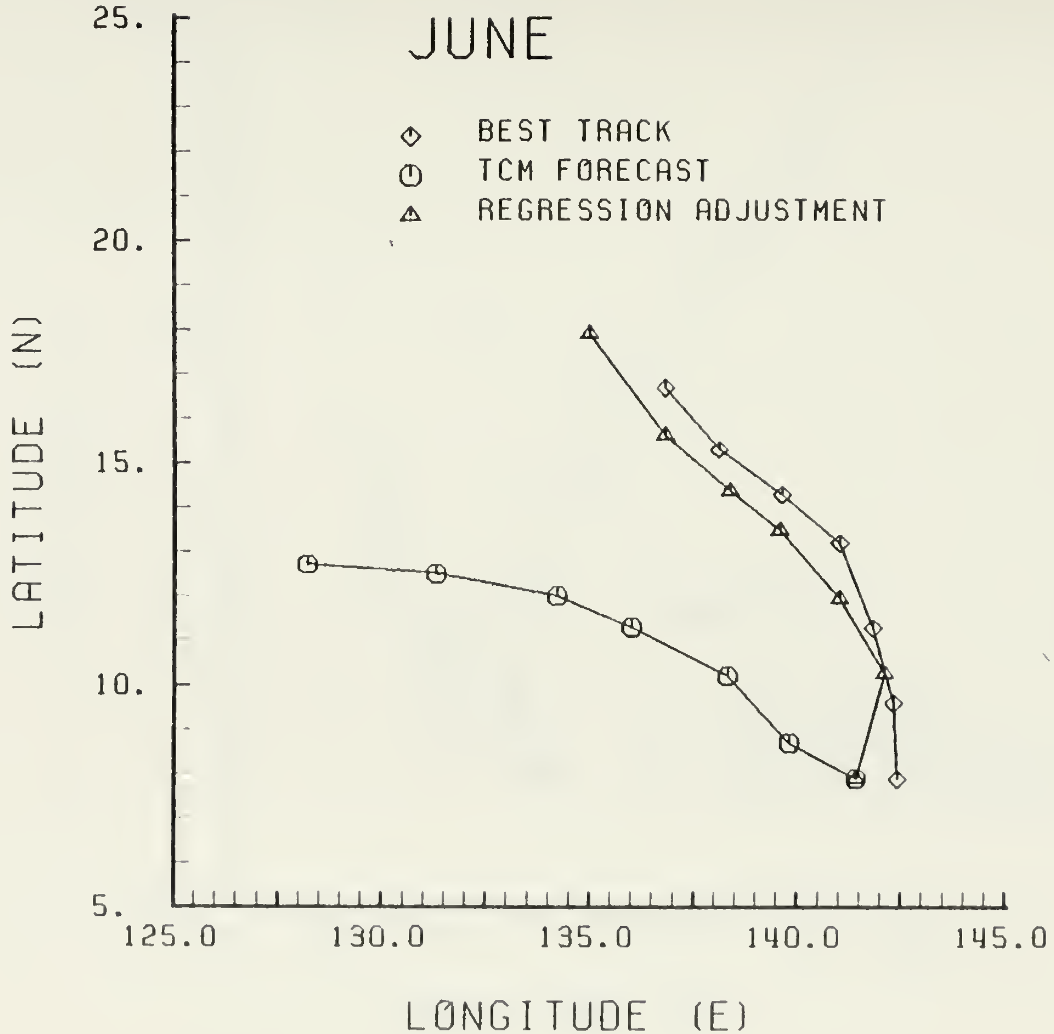


Figure 5. Unmodified TCM forecast tracks and regression-adjusted tracks of Typhoon June (18 Nov 75, 00 GMT) compared to best track positions. The interval between adjacent positions is 12 hours.

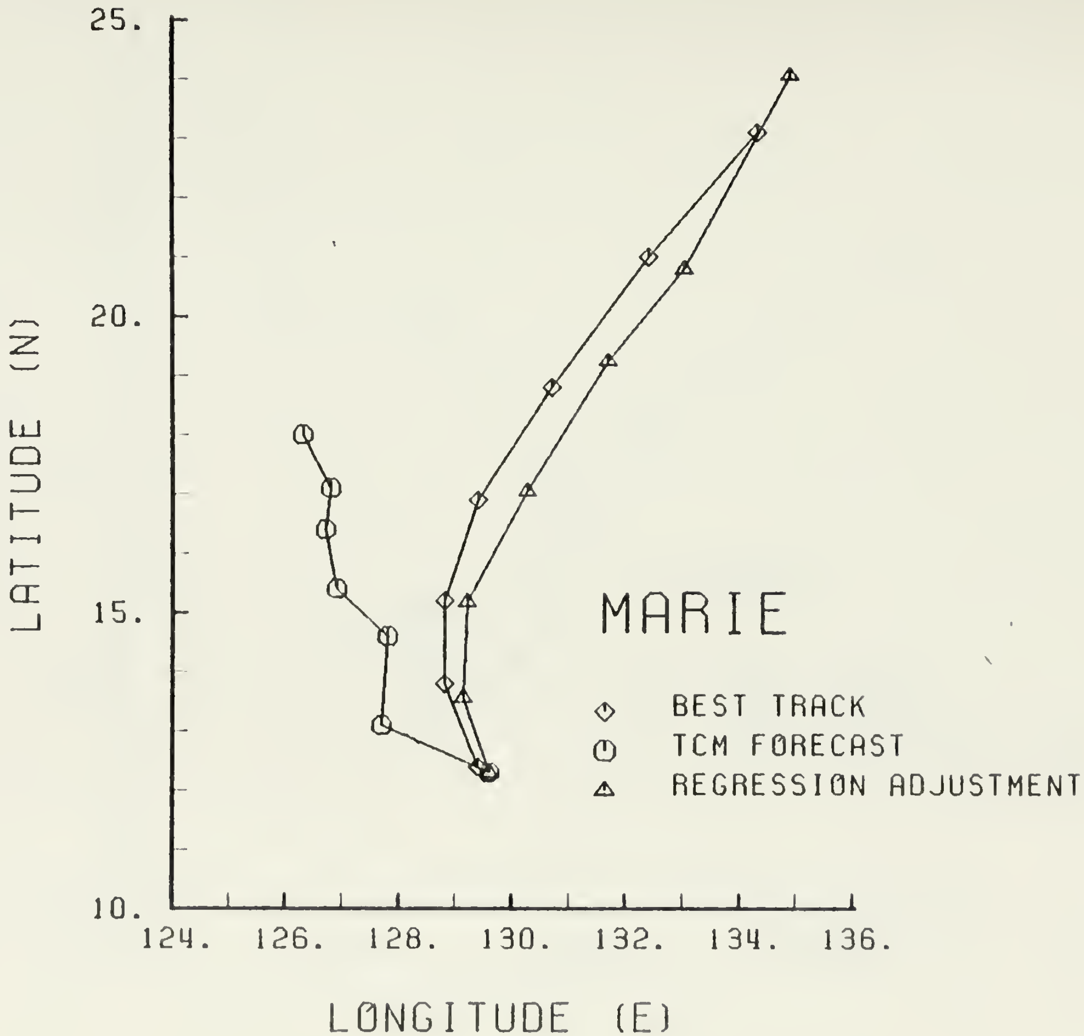


Figure 6. Typhoon Marie (10 Apr 76, 00 GMT), otherwise the same as Fig. 5.

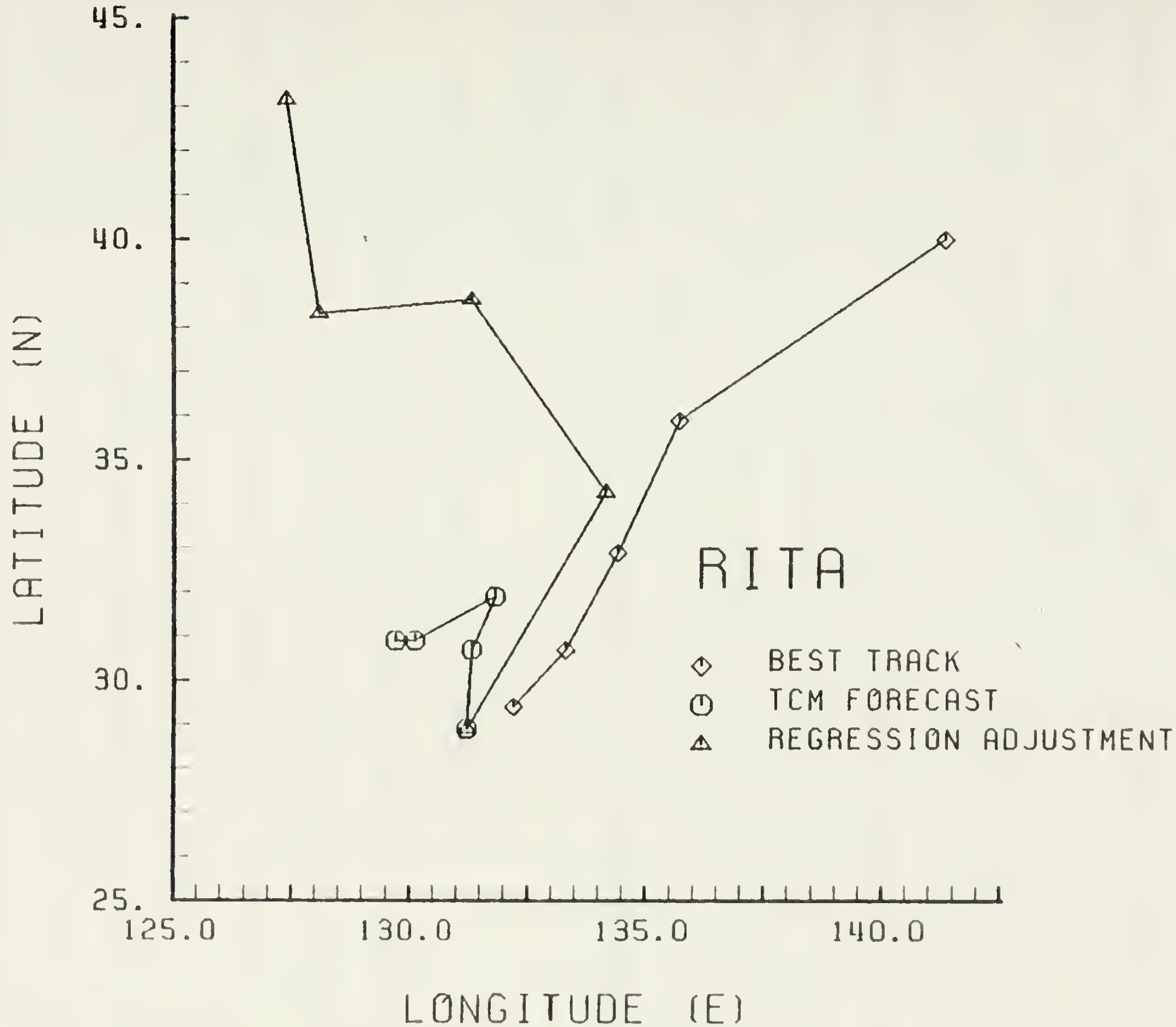


Figure 7. Typhoon Rita (21 Aug 75, 12 GMT), otherwise the same as Fig. 5.

indicates how small TCM velocities, as well as radical changes in the forecast storm track, will result in a regression-adjusted track with extremely high velocities and unrealistic variations in the storm path. This behavior of the regression equations seems to indicate that obviously erroneous regression positions can be used as a basis to reject TCM forecast positions as well.

The mean forecast errors of the 1975-76 dependent test sample are listed in Table IV. The sample improved on the forecast errors of both JTWC and the unmodified TCM forecasts for 1975-76. At 72 hours with a sample size of 28, the regression equation errors were also less than the U.S. Navy 7th Fleet goal of 150 nm. However, it is not expected that this pattern would be repeated in an independent sample of typhoon cases.

B. INDEPENDENT TEST OF FIRST EQUATION SET

An independent sample of 44 cases from the 1977-78 typhoon seasons was then used to test the regression equations derived from the 1975-76 cases discussed in the previous section. As indicated by the statistics in Table V, the results of the independent test were generally very poor. In each category the modified TCM tracks were worse than the unmodified tracks. The large errors are attributed to the unstable nature of the regression equations from the small and very homogeneous sample of anomalous storm tracks used to derive the regression equations. This led to excessive velocities and erratic tracks in the regression-adjusted

TABLE IV

Mean forecast errors (nm) based on the best tracks for 1975 and 1976. Errors incurred by the unmodified TCM and the regression-modified TCM are shown with the combined 1975-76 JTWC errors and the U.S. Navy 7th Fleet goal for forecast errors.

	7th Fleet Error Goal	JTWC Errors 1975-76	Unmodified TCM 1975-76	Modified TCM(*) 1975-76	Sample Size 1975-76
24 hr	50	121	126	102	46
48 hr	100	241	252	156	39
72 hr	150	366	366	96	28

(*) dependent test

TABLE V

Mean forecast errors (nm) based on the best tracks for 1977 and 1978. Errors incurred by the unmodified TCM and the regression-modified TCM are shown with dependent test results for 1975-76 and the U.S. Navy 7th Fleet goal for forecast errors. The same regression equations were used in the modified TCM positions for 1975-76 and 1977-78.

	7th Fleet Error Goal	Modified TCM(*) 1975-76	Unmodified TCM 1977-78	Modified TCM(**) 1977-78	Sample Size 1975-78
24 hr	50	102	132	180	44
48 hr	100	156	282	372	39
72 hr	150	96	450	648	33

(*) dependent test (from Table IV)

(**) independent test

storm positions for 1977-78. When the TCM forecasts had large deviations from the best track, the regression positions incurred commensurately larger errors. It was clear that the number of TCM forecast cases had to be increased as much as possible to increase the stability of the regression equations.

The regression equations used in these tests did not improve storm positions by taking advantage of the systematic errors of the TCM, which is often too slow and to the left of the best track. Typhoon Lola is depicted in Fig. 8 and indicates slight corrective shifting of the regression positions to the right of the TCM forecast track. However, overcompensation is again evident in the velocity components. More typical of the independent test results is the adjusted track for Typhoon Lucy shown in Fig. 9. Velocity errors were large and the track was erratic. In many cases in the independent test, an erratic track, such as the regression-adjusted path for Typhoon Lucy, occurred when the unmodified TCM forecast track also incurred large errors. The single redeeming feature of these 1975-76 equations may be that highly erratic regression positions could be indicative of a poor TCM forecast. This information may be useful in leading the typhoon forecaster to reject both the modified and the unmodified TCM guidance in making his decision.

C. SECOND EQUATION SET BASED ON FORWARD INTEGRATION

The second set of regression equations was obtained from the combined storm cases in the 1975-76 and 1977-78 samples.

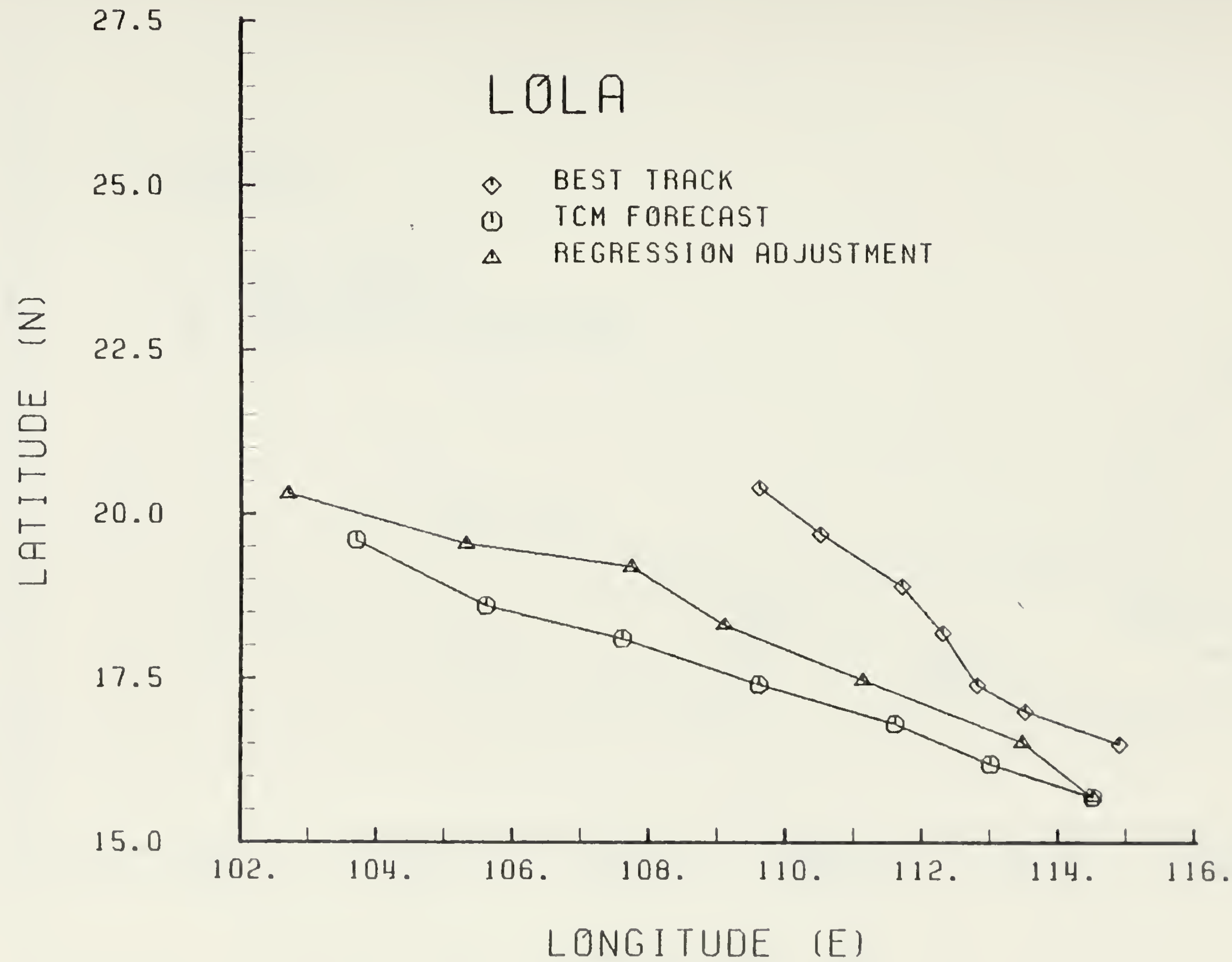


Figure 8. Typhoon Lola (29 Sep 78, 00 GMT), otherwise the same as Fig. 5.

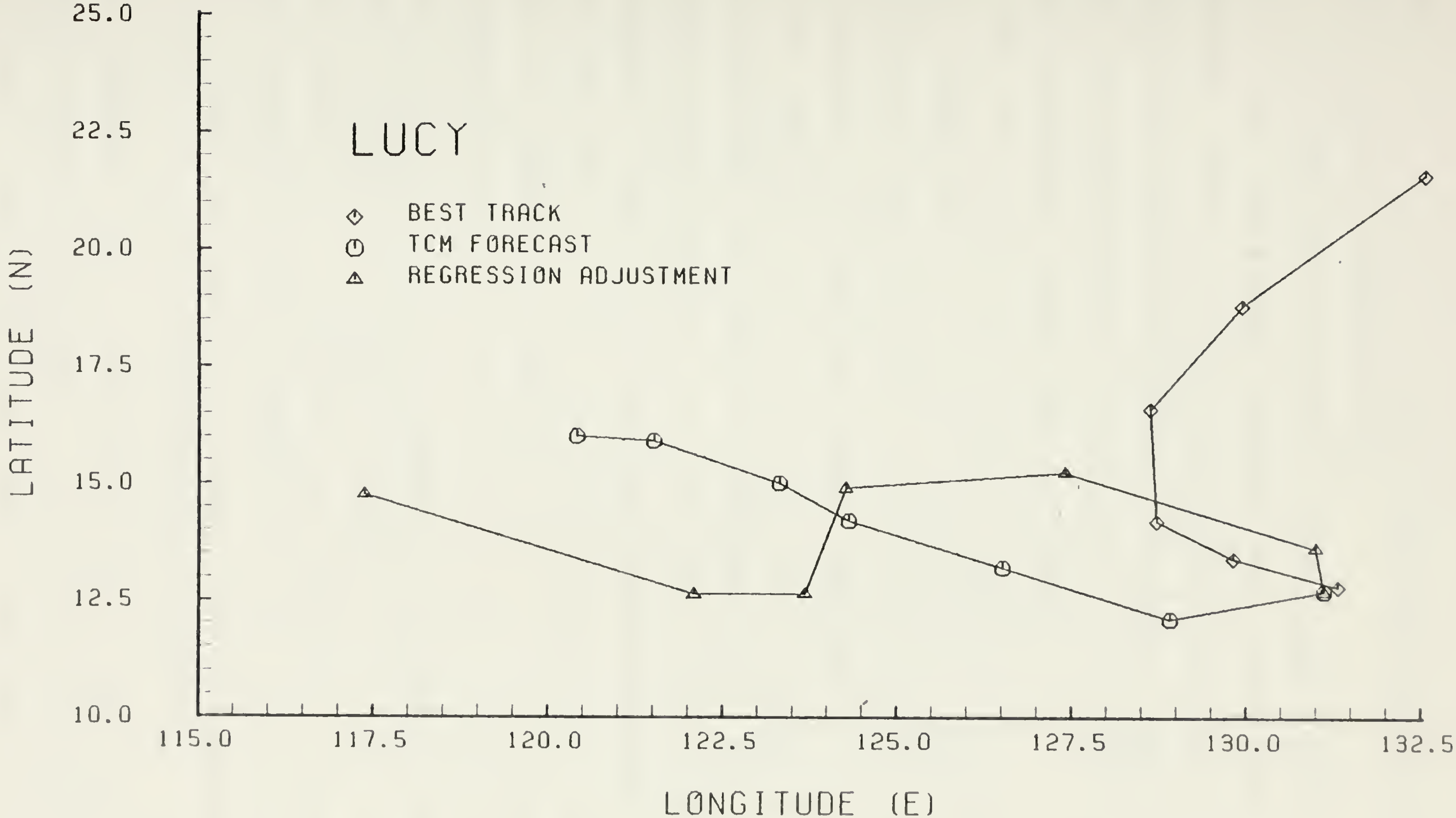


Figure 9. Typhoon Lucy (03 Dec 77, 00 GMT), otherwise the same as Fig. 5.

Because this exhausts the sample, these equations can only be evaluated as a dependent test.

This second set of equations, with a larger sample of 61, was more stable overall than the first set of regression equations. While the regression-adjusted positions still increase the velocity excessively, the apparent result is that this overcompensation is decreased in the 1975-78 regression equations versus those for 1975-76.

The five typhoon cases shown previously in Fig. 5 through Fig. 9 appear again in Fig. 10 through Fig. 14, but this time illustrating the regression-adjusted positions of the 1975-78 equations. The track for Typhoon June shown in Fig. 10 was not adjusted as well in this test, but it serves to illustrate that the regression adjustments cannot always compensate for the tendency of the TCM to not predict recurvature. Presumably if the TCM track had been more northwesterly, the adjustment would have been toward more recurvature. The track for Typhoon Marie depicted in Fig. 11 still indicates a reasonable adjustment for recurvature, but has incurred a marked decrease in velocity adjustment. Although the adjusted speed of movement for Typhoon Rita shown in Fig. 12 is slower than that on Fig. 7, the track is not significantly changed from the previous result. However, this case again suggests that a radical and obviously erroneous regression adjustment may serve as a basis to reject the TCM forecast also. Typhoon Lola (September 1978), illustrated in Fig. 13, has a much improved regression adjustment of the storm track compared with Fig. 8. The velocity corrections in this case are much

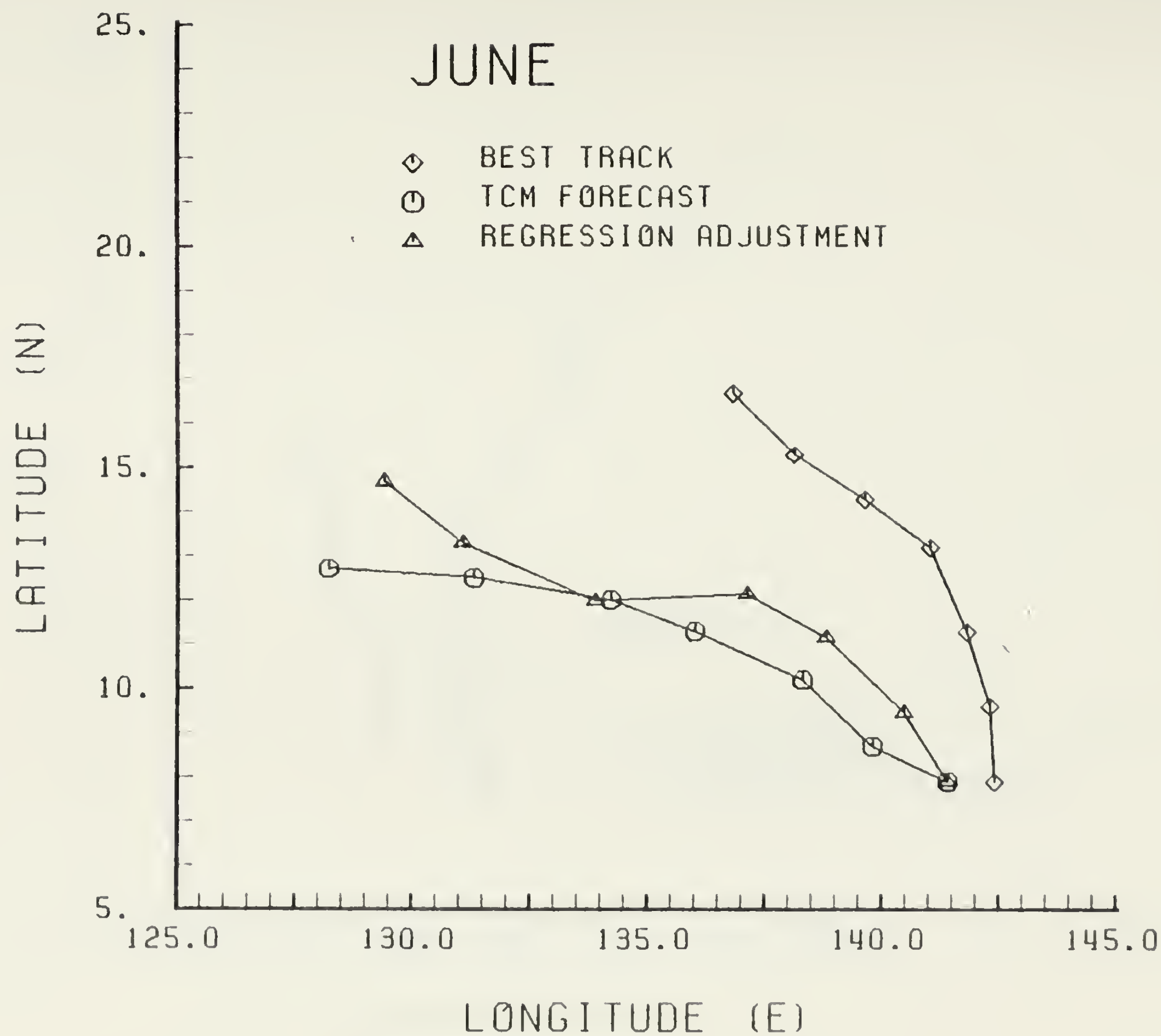


Figure 10. Typhoon June (18 Nov 75, 00 GMT), otherwise the same as Fig. 5.

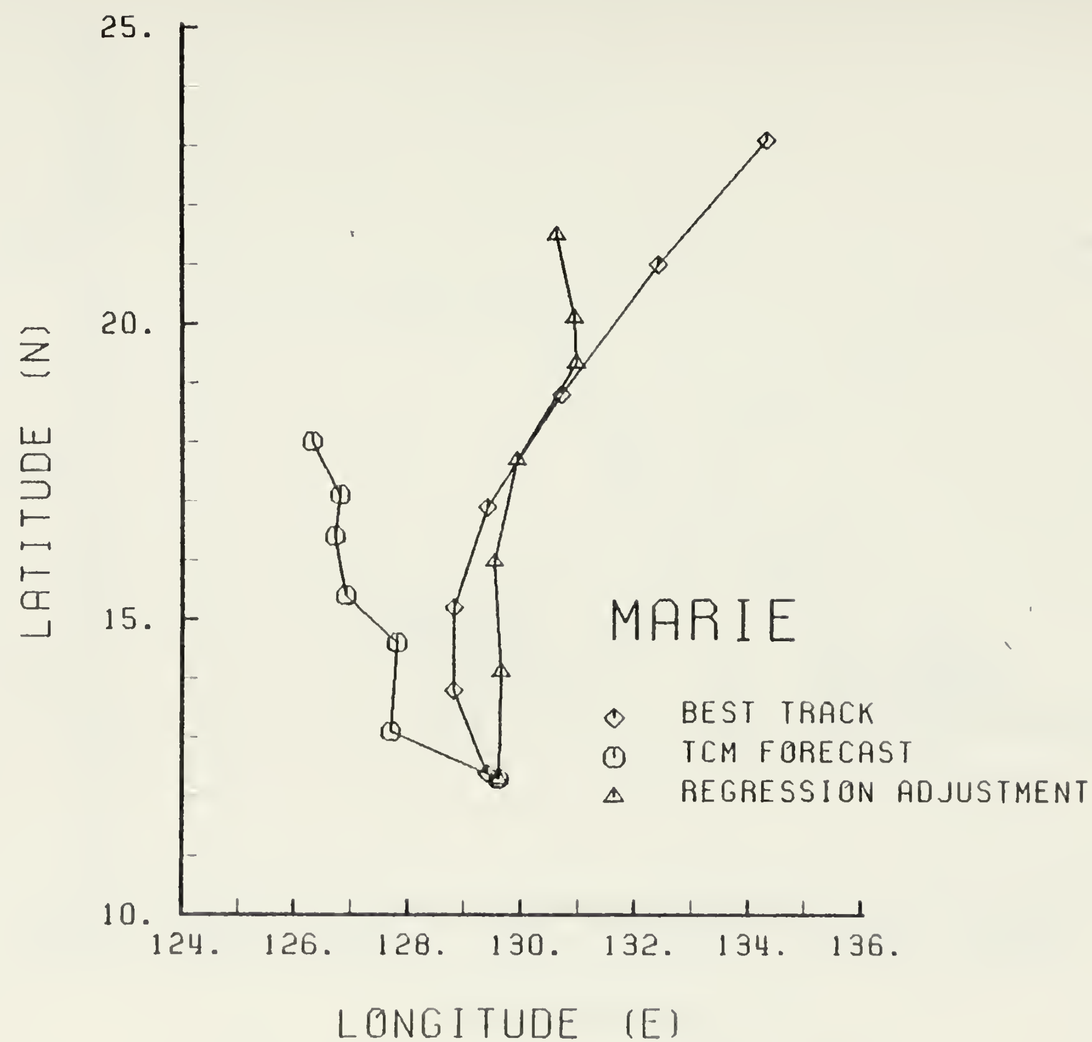


Figure 11. Typhoon Marie (10 Apr 76, 00 GMT), otherwise the same as Fig. 5.

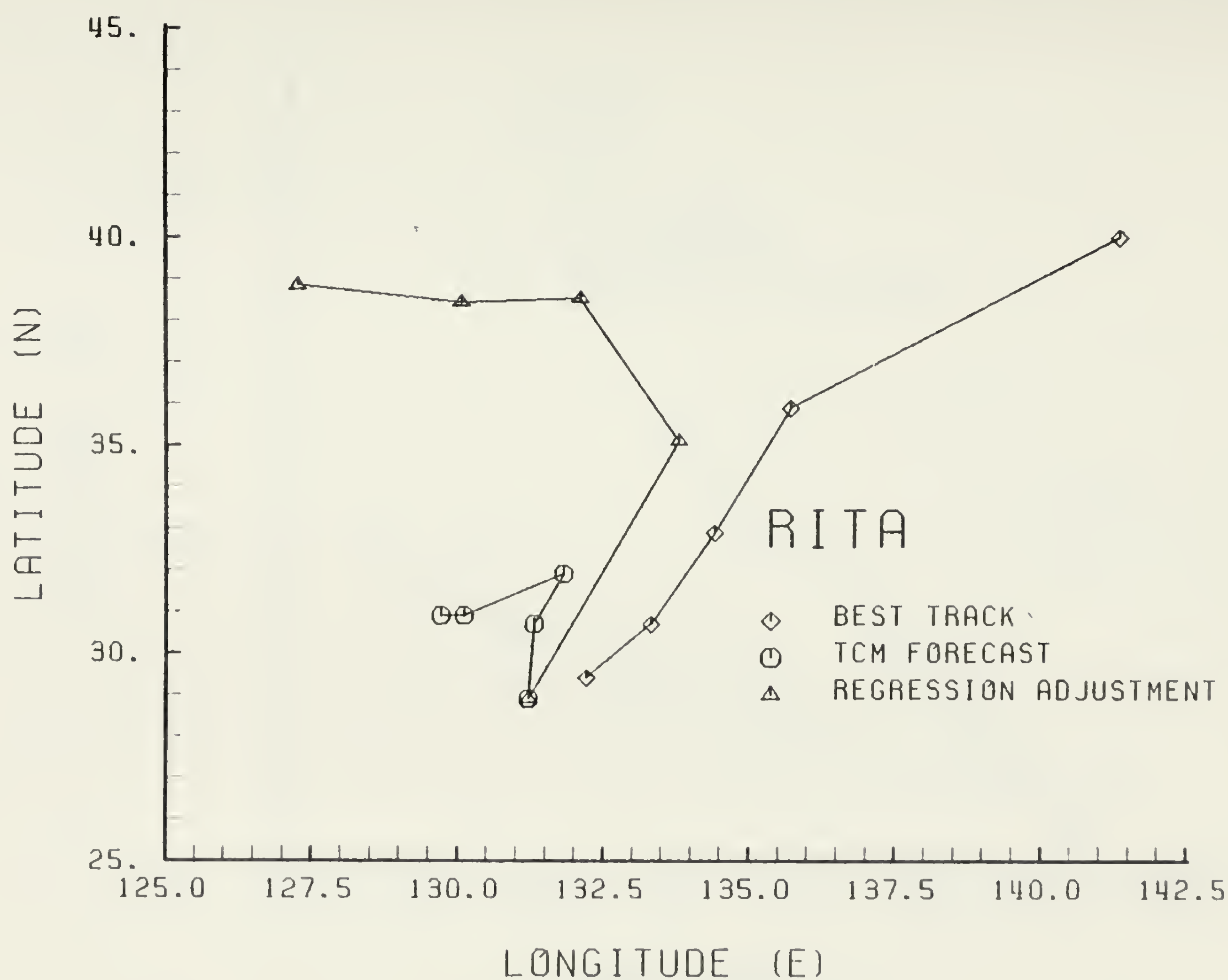


Figure 12. Typhoon Rita (21 Aug 75, 12 GMT), otherwise the same as Fig. 5.

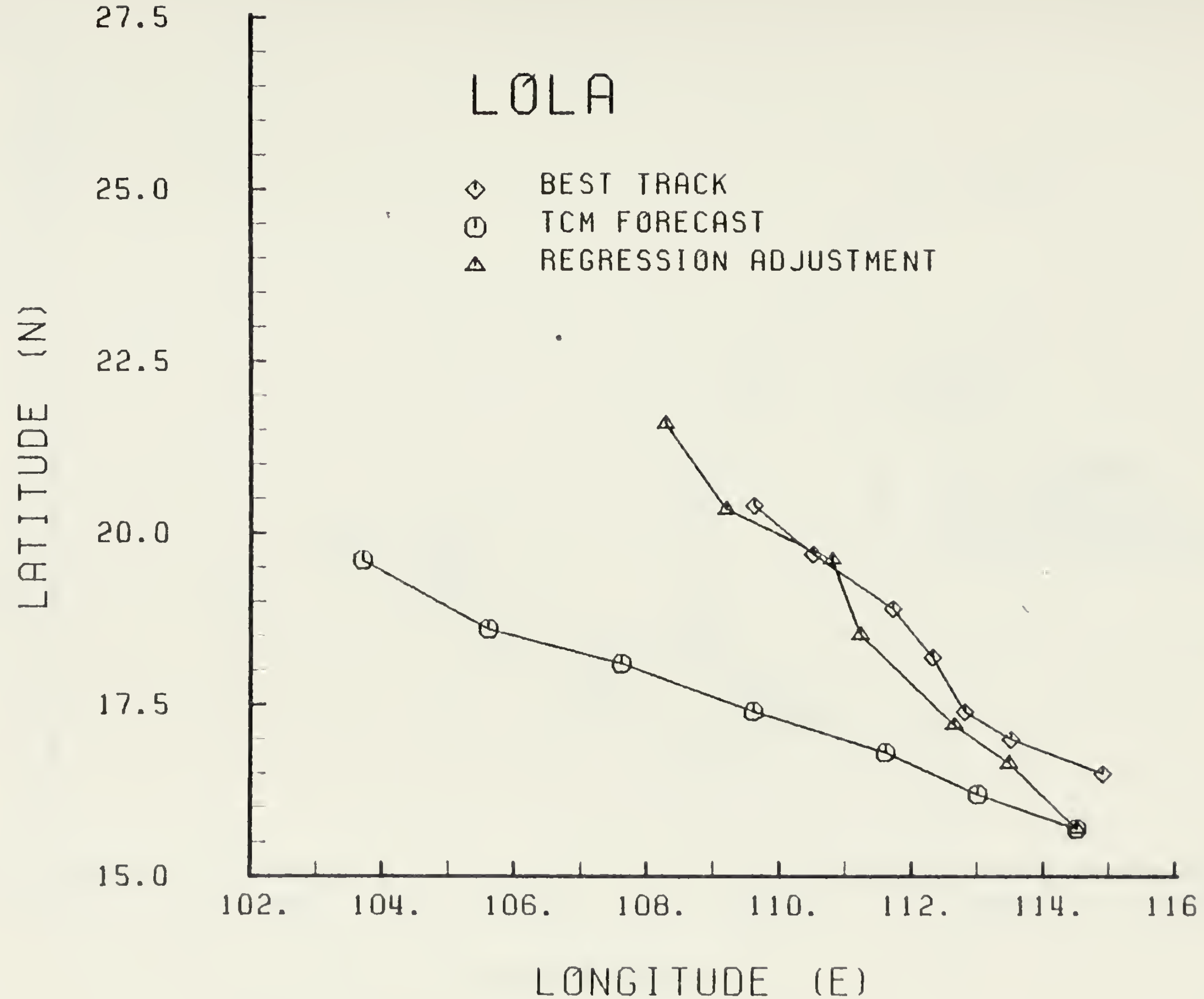


Figure 13. Typhoon Lola (29 Sep 78, 00 GMT), otherwise the same as Fig. 5.

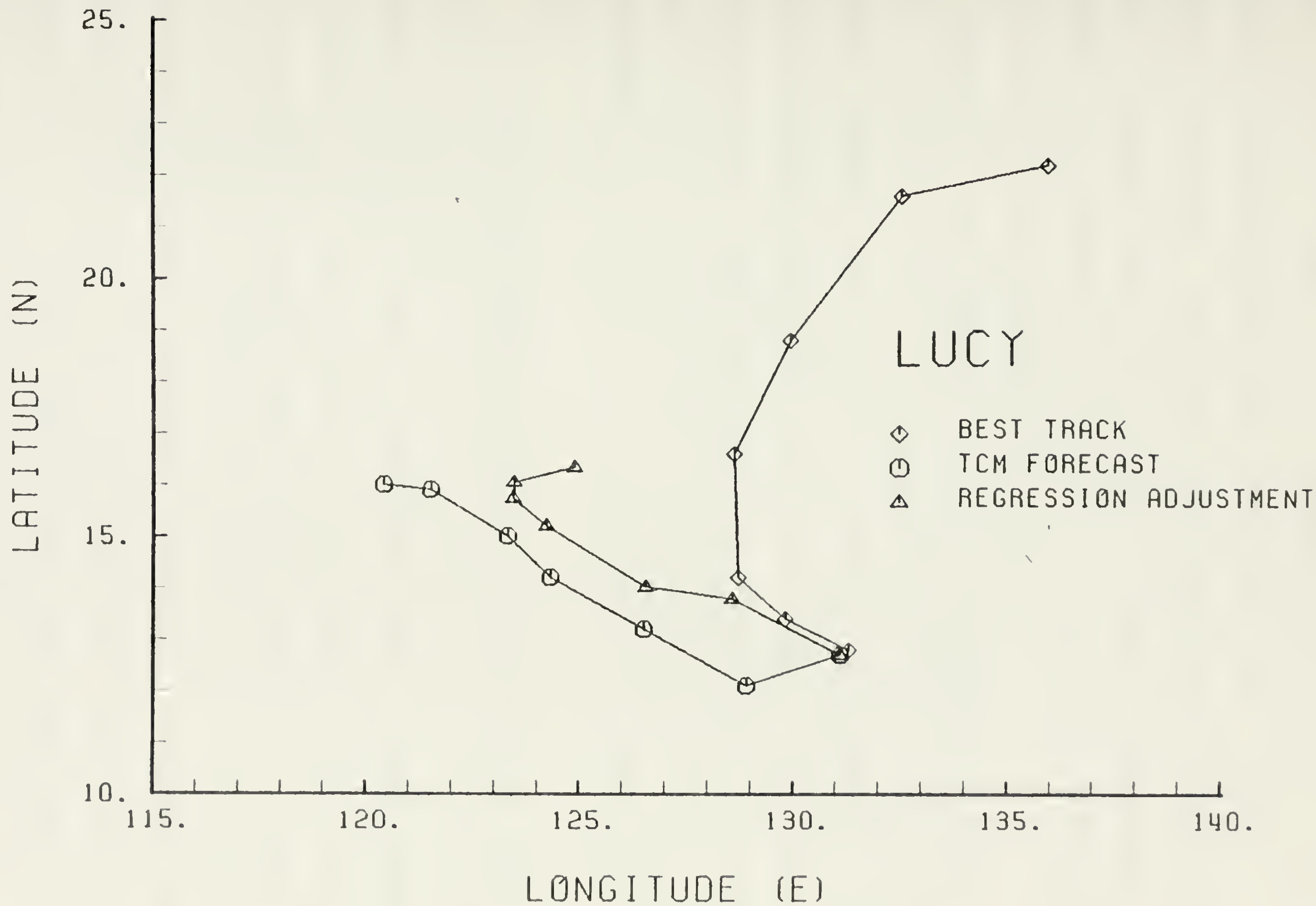


Figure 14. Typhoon Lucy (03 Dec 77, 00 GMT), otherwise the same as Fig. 5.

closer to the actual velocities which appear in the best track positions. The adjusted track for Typhoon Lucy is shown in Fig. 11 and is to be compared with Fig. 9. The regression-adjusted positions are still poor, but not nearly as erratic. Note that the regression-modified positions do suggest some recurvature, although inaccurately, and that the decreased velocities are much more realistic with the 1975-78 regression equations.

Generally, the results of these experiments suggest that a further increase in the number of TCM forecasts in the data sample would lead to a further improvement in the regression-modified storm positions. Overall, the errors incurred by the regression-adjusted tracks were less than those of the unmodified TCM storm path (see Table VI). The improvements are especially noteworthy at 48 hours and 72 hours.

In forecasting typhoons which tracked westward, the unmodified TCM forecast positions usually proved to be very accurate, with the regression-modified path seldom improving on the TCM. One case (Typhoon Rita, October 1978) in which the regression equations improved the forecast is shown in Fig. 15. The improvement is the result of an increase in storm velocity by the regression equations. Several other examples of enhanced track predictions are shown in Fig. 16 through Fig. 18. These examples show some improvement in direction, but the improvement in speed of movement is especially rewarding.

TABLE VI

Mean forecast errors (nm) based on the best tracks for 1975 through 1978. Errors incurred by the unmodified TCM and the regression-modified TCM are shown with the U.S. Navy 7th Fleet goal for forecast errors.

	7th Fleet Error Goal	Unmodified TCM 1975-78	Modified TCM(*) 1975-78	Sample Size 1975-78
24 hr	50	132	114	90
48 hr	100	270	192	78
72 hr	150	414	276	61

(*) dependent test

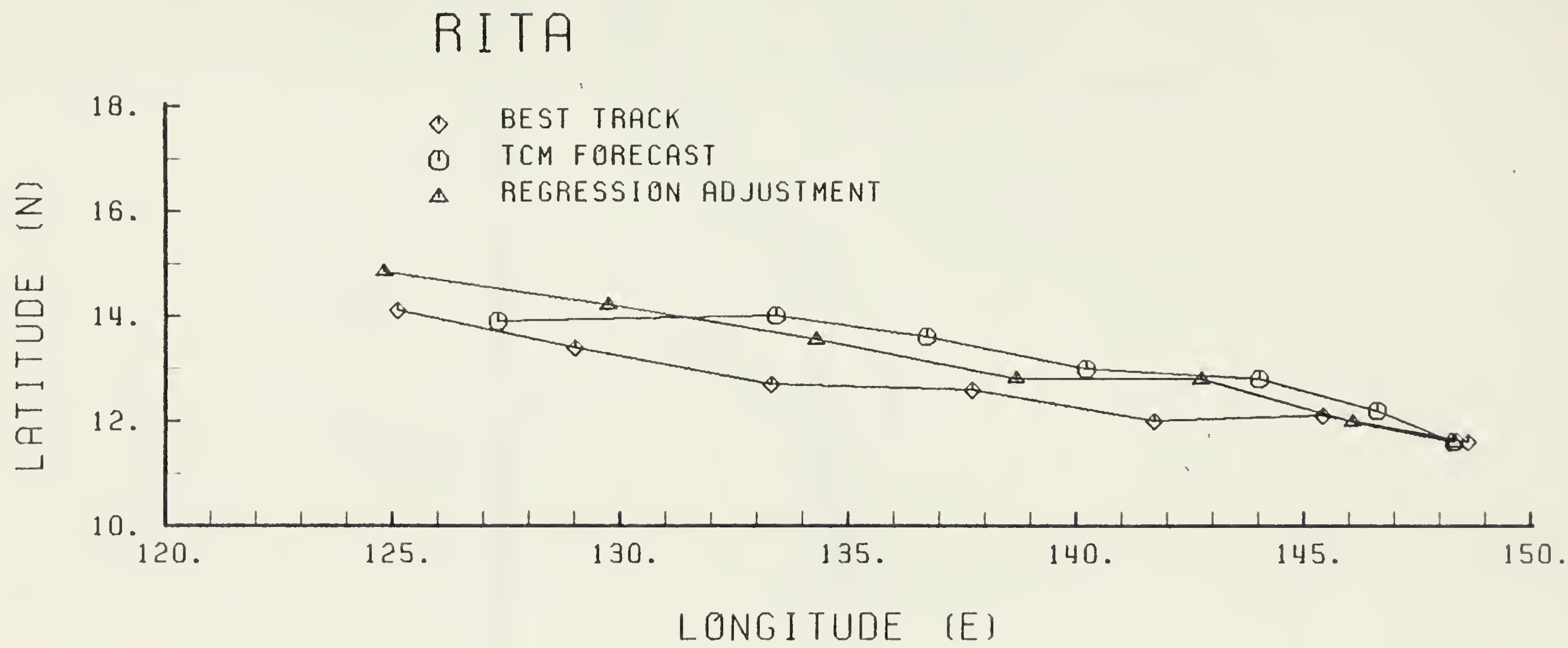


Figure 15. Typhoon Rita (23 Oct 78, 00 GMT), otherwise the same as Fig. 5.

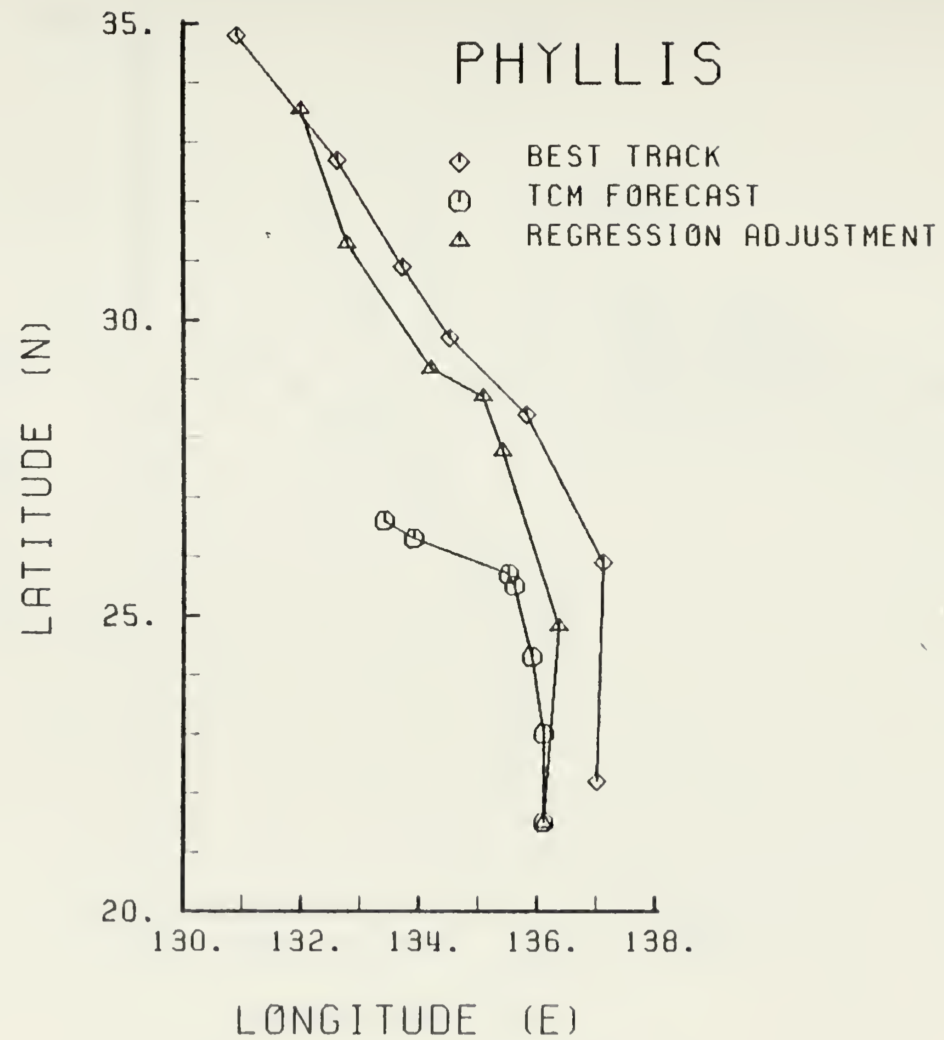


Figure 16. Typhoon Phyllis (14 Aug 75, 12 GMT), otherwise the same as Fig. 5.

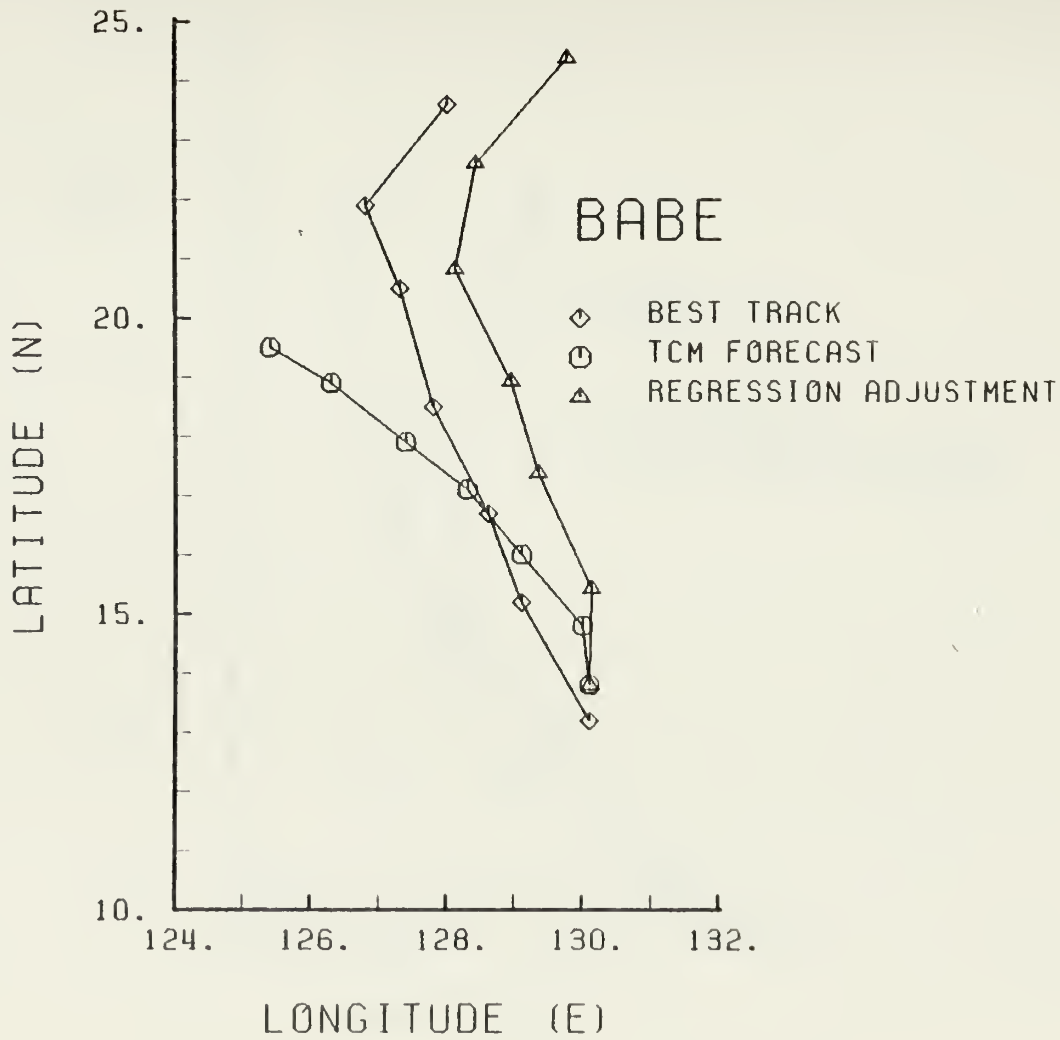


Figure 17. Typhoon Babe (06 Sep 77, 00 GMT), otherwise the same as Fig. 5.

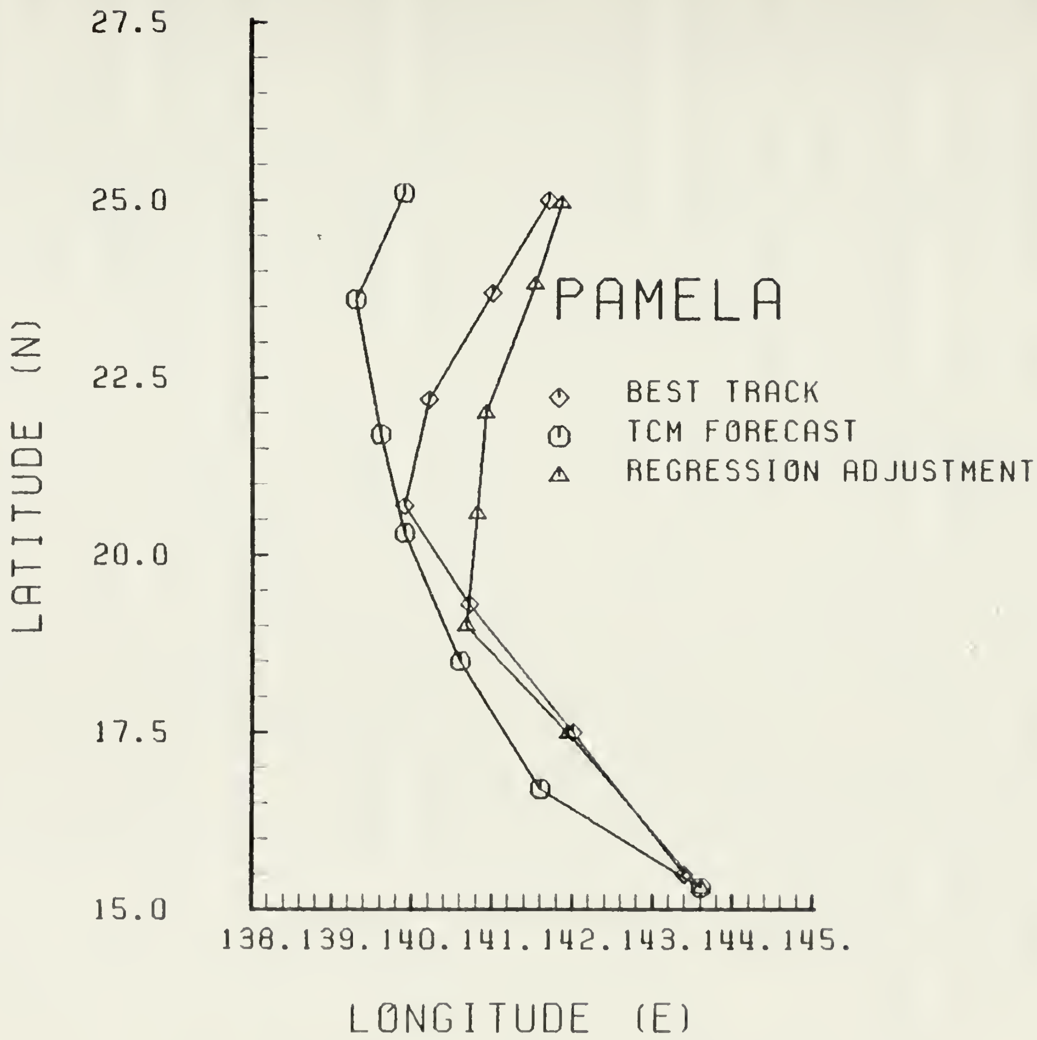


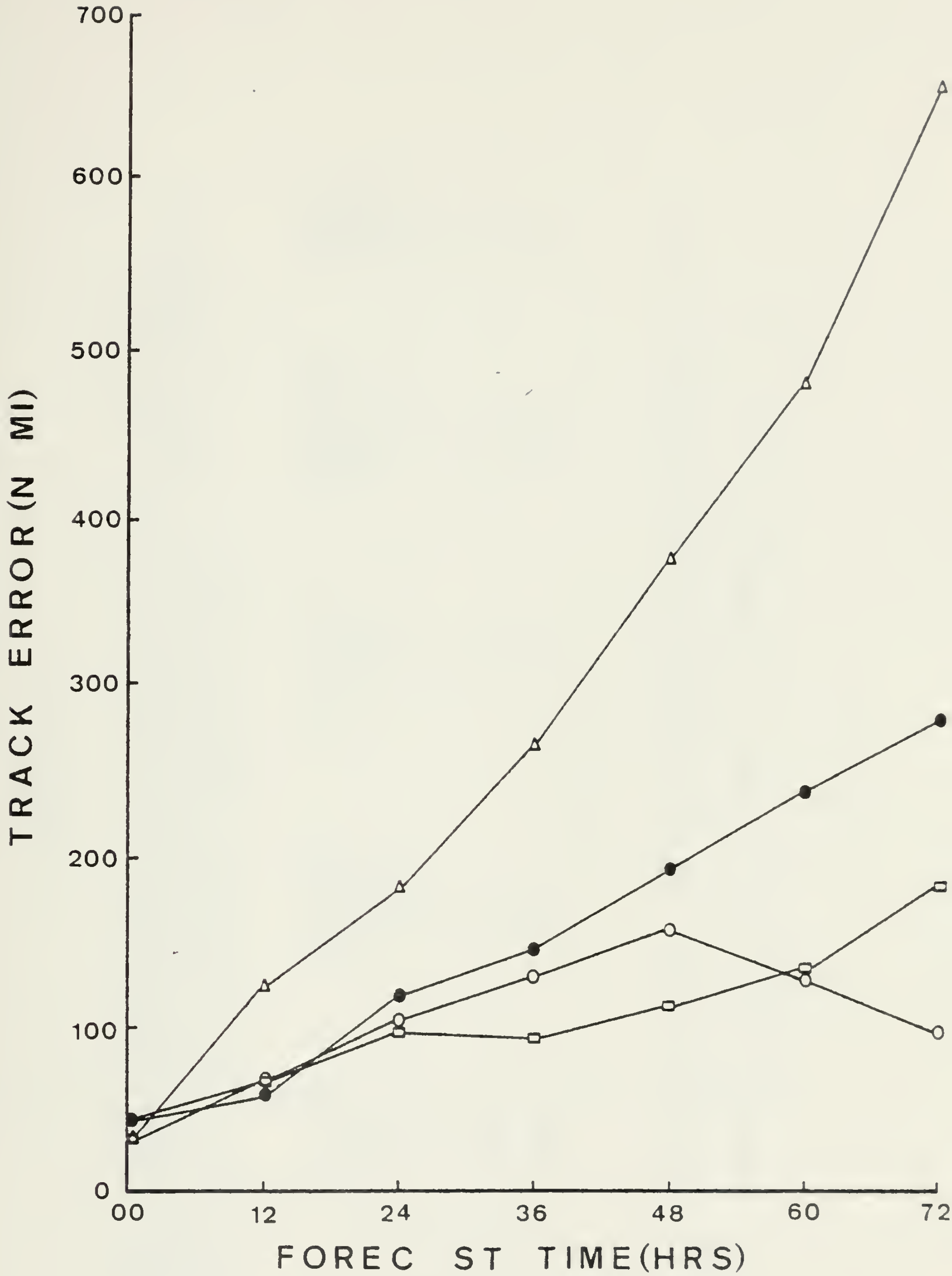
Figure 18. Typhoon Pamela (22 May 76, 00 GMT), otherwise the same as Fig. 5.

D. EQUATION SET BASED ON FORWARD AND BACKWARD INTEGRATION

These experiments with the 1977-78 typhoon cases were performed to test the regression equations derived from the 1977-78 data set which included backward-integrated positions to -36 hours. As the complete set of backward tracks was used in the derivation of the regression equations, these experiments refer only to the dependent sample.

The results of the dependent test with forward- and backward-integrated positions were the best of all experiments conducted during this research. This equation set incurred the lowest mean errors overall (see Fig. 19). The regression-modified storm position errors are very close to meeting the U.S. Navy 7th Fleet error goal (see Table VII).

Tracks for Typhoons Lola, Rita, and Babe shown previously in Fig. 13, 15, and 17, respectively, appear again in Fig. 20 through Fig. 22 with adjusted positions based on forward-backward integration. Typhoon Lola (September 1978), shown in Fig. 20, is more erratic than the same case (Fig. 13) using regression equations based only on forward integration. However, the regression positions that are based on forward-backward integration are fluctuating on either side of the best track. The variation about the best track is attributed primarily to the small size of the data set (31 cases) used to derive the equations. This "saw-tooth" variation about the best track is characteristic of the behavior storms which tracked westward in this experiment. As in previous tests, it proved difficult to improve on the unmodified TCM forecast positions when typhoons were tracking approximately westward.



A

Figure 19. Mean track error (nm) for the 1975-76 dependent test (O), the 1977-78 independent test (Δ), the 1975-78 dependent test (●), and the 1977-78 dependent test (□). The 1977-78 dependent test (□) was the only experiment which included backward integration.

TABLE VII

Mean forecast errors (nm) based on the best tracks for 1977 and 1978. Errors incurred by the unmodified TCM, the regression-modified TCM with only forward integration (*), and the regression-modified TCM with backwards integrated (**) are shown with the U.S. Navy 7th Fleet goal for forecast errors.

	7th Fleet Error Goal	Modified TCM(*) 1977-78	Unmodified TCM 1977-78	Modified TCM(**) 1977-78	Sample Size 1977-78
24 hr	50	180	138	96	38
48 hr	100	372	288	108	35
72 hr	150	648	474	180	31

(*) independent test, forward integration only (equation set #1)

(**) dependent test, with backward integration

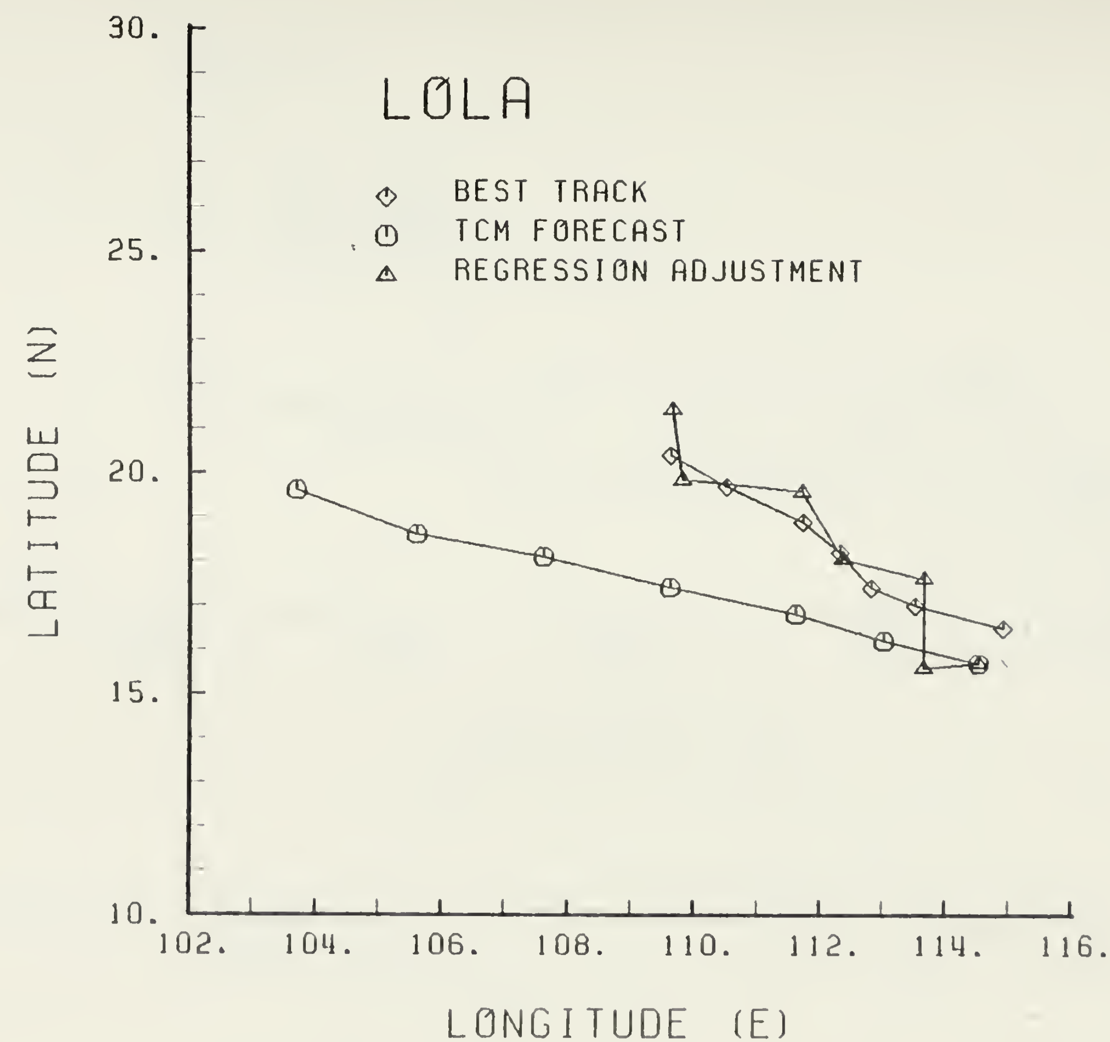


Figure 20. Typhoon Lola (29 Sep 78, 00 GMT), otherwise the same as Fig. 5.

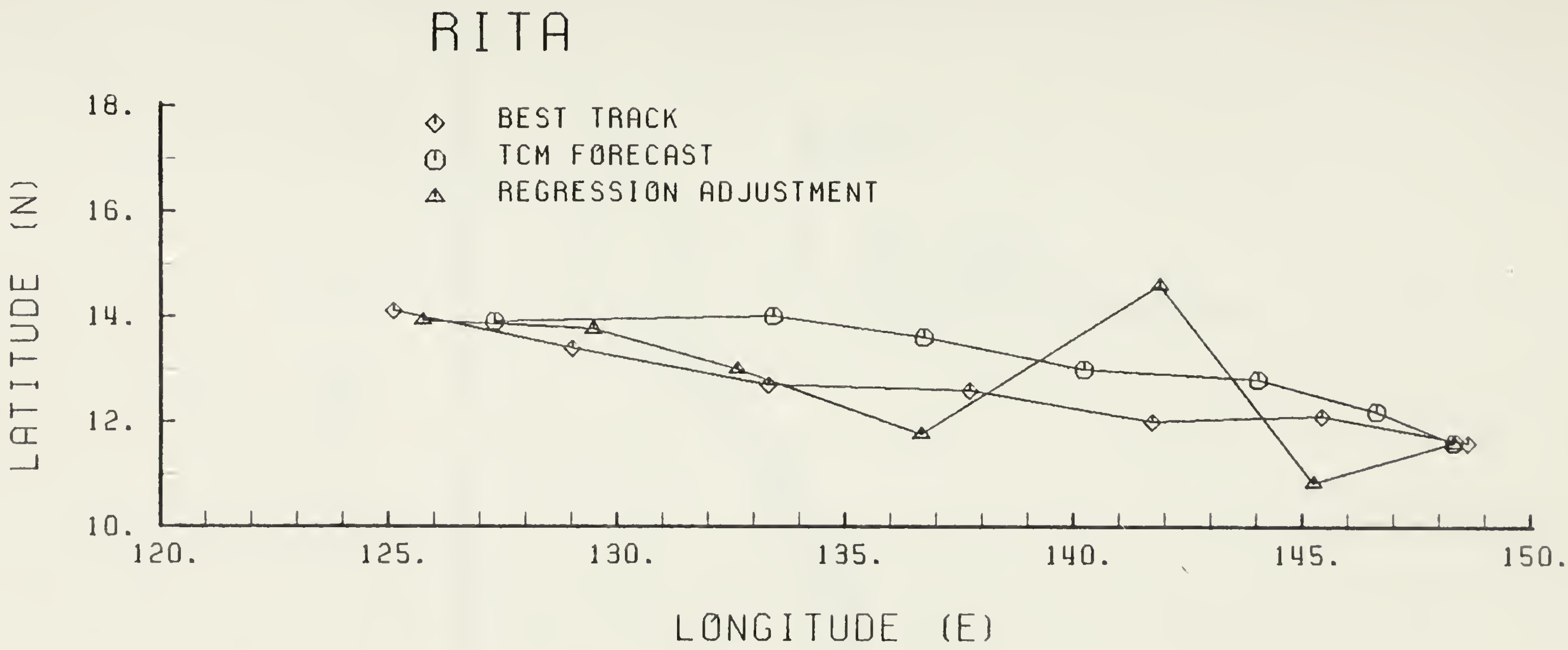


Figure 21. Typhoon Rita (23 Oct 78, 00 GMT), otherwise the same as Fig. 5.

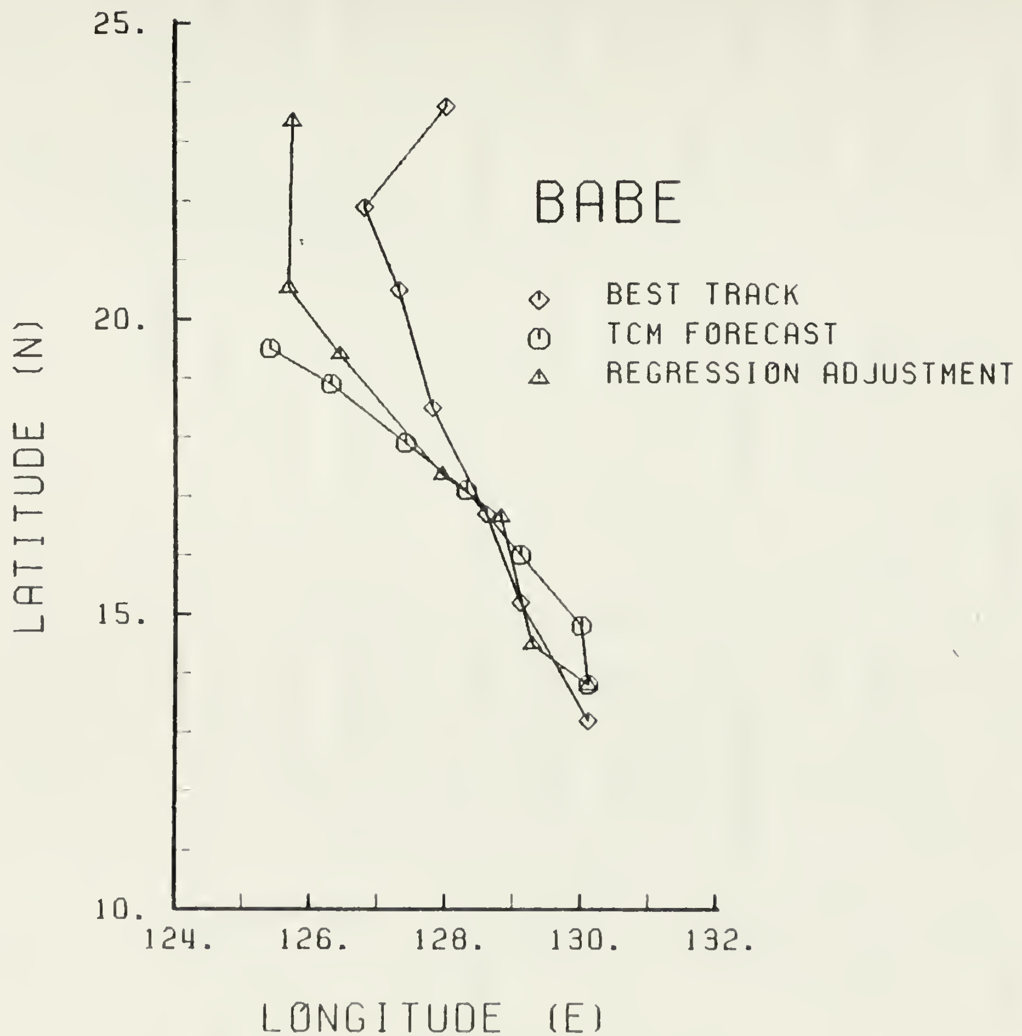


Figure 22. Typhoon Babe (06 Sep 77, 00 GMT), otherwise the same as Fig. 5.

The adjusted track of Typhoon Rita in Fig. 21 exhibits a similar behavior in another westward tracking storm, but does very well in the longitudinal positioning of the storm. Adjustment of the track of Typhoon Babe, shown in Fig. 22, has improved the velocity forecast as well as has indicated some recurvature which the TCM missed (see also Fig. 17).

Typhoon Phyllis is illustrated in Fig. 23. It provides an excellent forecast of recurvature not achieved by the unmodified TCM forecast or by the regression equations based only on forward integration of the TCM. The velocities indicate only a slight tendency to overcompensate for the slower TCM forecast. Recurvature of Typhoon Gilda, depicted in Fig. 24, is correctly predicted, but the velocities are excessive. Adjustment of the track of Typhoon Wendy as in Fig. 25 showed slight improvement over the unmodified TCM positions. The interesting feature in the regression-adjusted path is the indication that the storm would reverse its direction. Within 12 hours of the indicated time, Typhoon Wendy did change direction in this manner, but with somewhat smaller displacements.

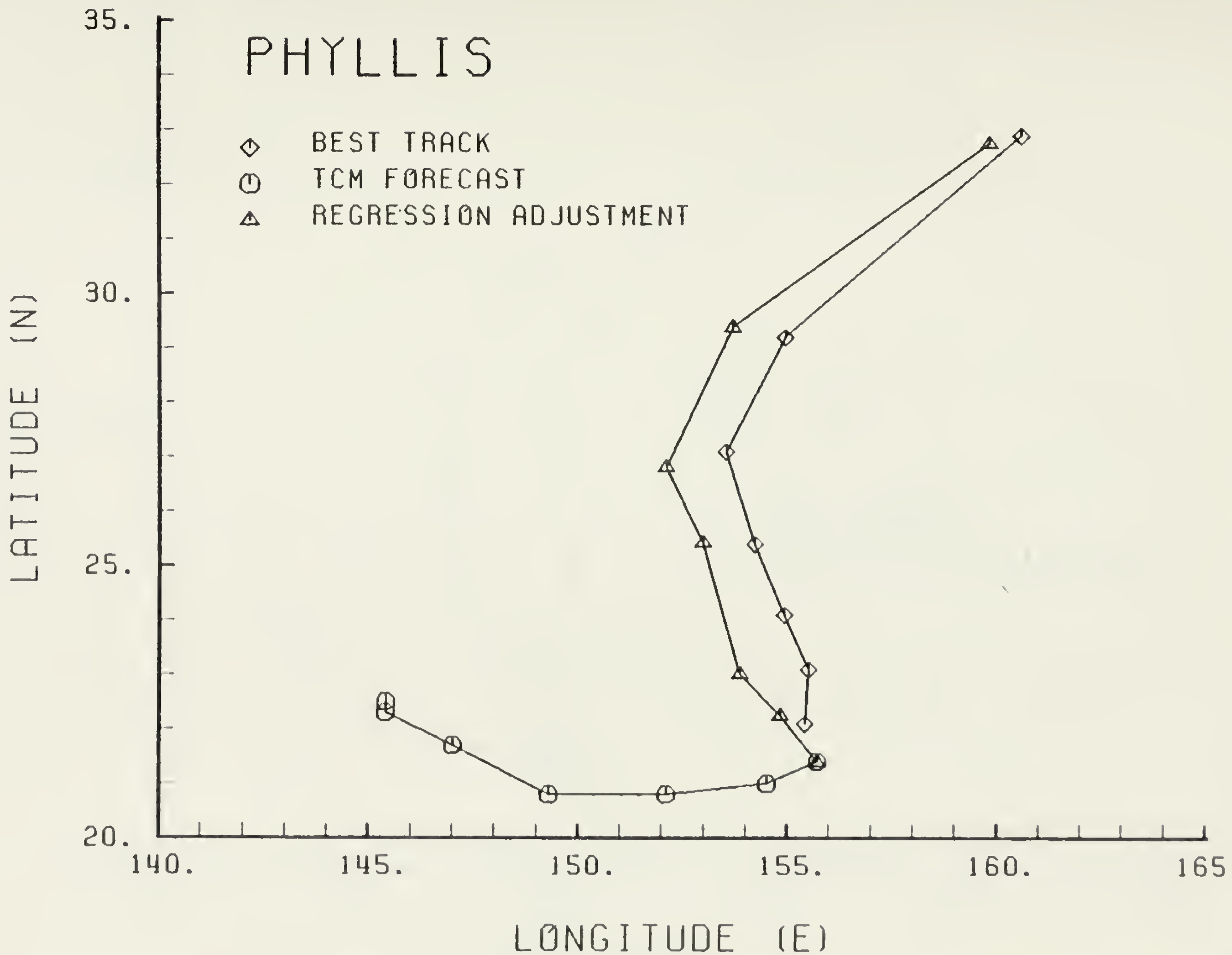


Figure 23. Typhoon Phyllis (19 Oct 78, 00 GMT), otherwise the same as Fig. 5.

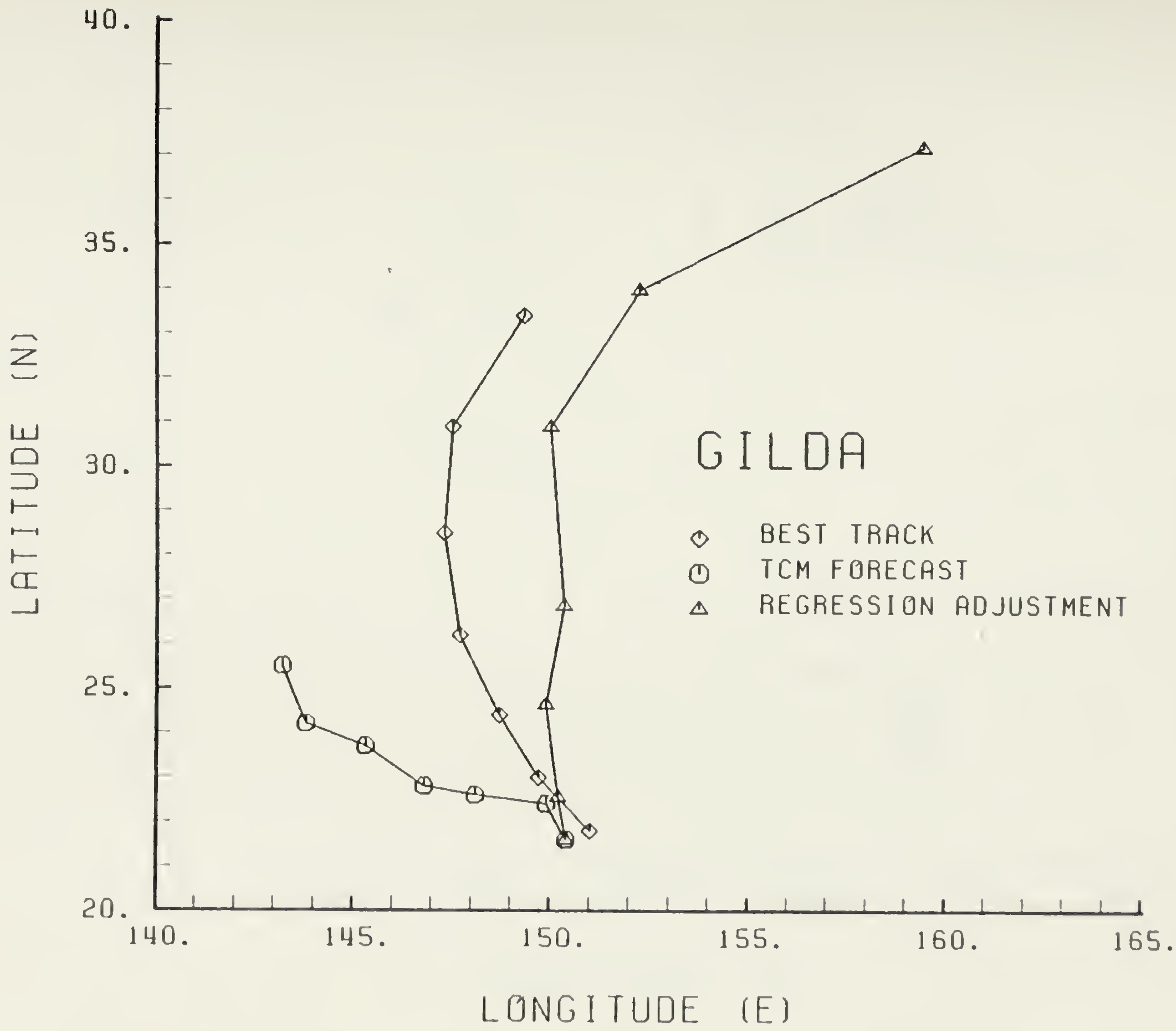


Figure 24. Typhoon Gilda (05 Oct 77, 12 GMT), otherwise the same as Fig. 5.

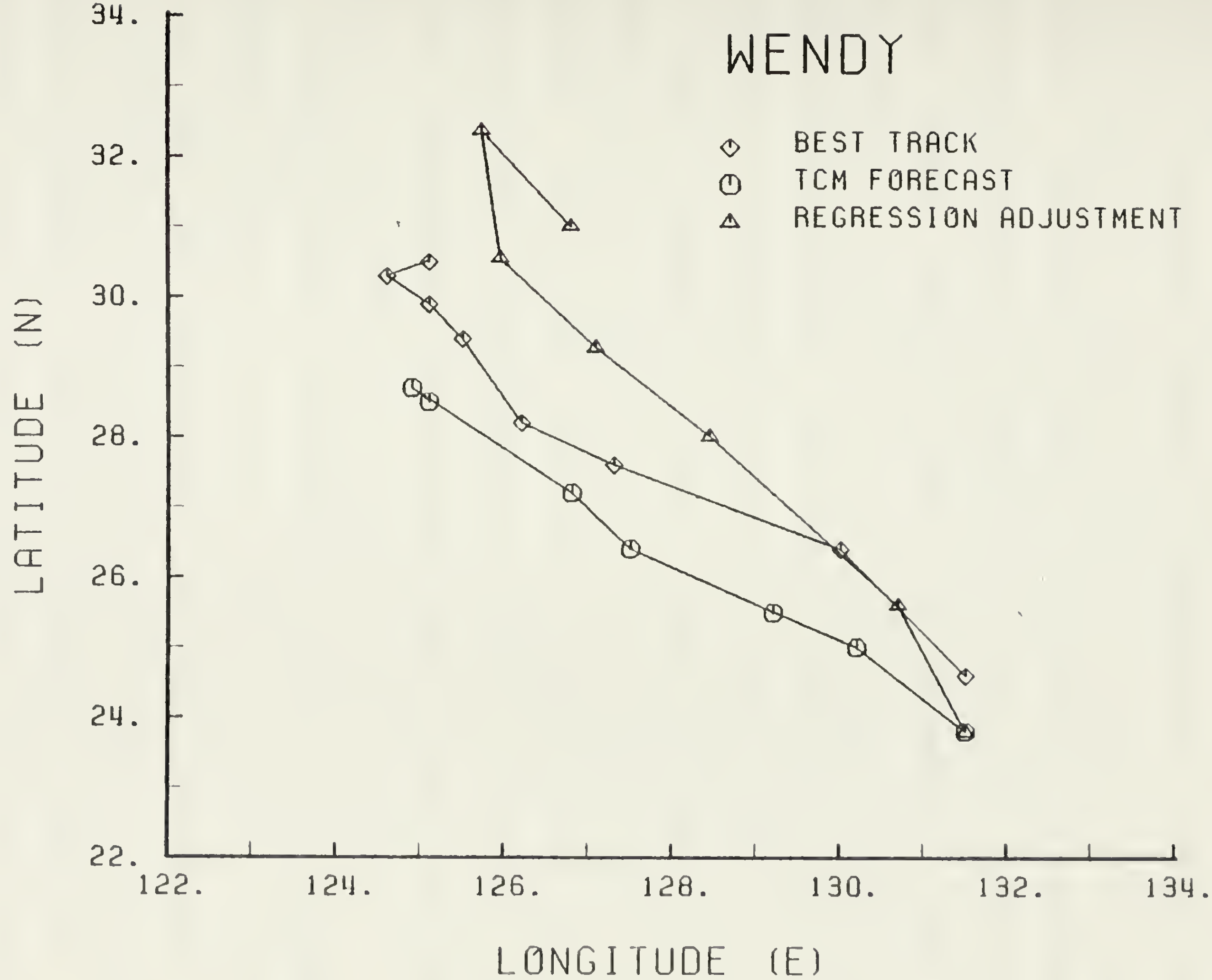


Figure 25. Typhoon Wendy (27 Jul 78, 12 GMT), otherwise the same as Fig. 5.

VI. CONCLUSIONS

A three-layer, primitive-equation model (Hodur and Burk, 1978) with one-way interactive boundaries is being tested at the Naval Environmental Prediction Research Facility (NEPRF). The objective of this research was to generate statistical regression equations to adjust the TCM-predicted tracks towards the best tracks. This approach is based on the assumption that it is possible to adjust for systematic model and data errors. Development consisted of deriving three sets of regression equations, with two sets based only on forward integration of the TCM, while the last set contained predictors based on both forward and backward integration. All TCM runs were based on operationally analyzed data from FNWC. Time-dependent boundary conditions provided to the TCM were derived from analyzed (rather than predicted) fields, as was the case in Hodur and Burk (1978).

The most notable improvements occured with the regression equations containing predictors based on backward integration of the TCM. The equations with predictors having both forward- and backward-integrated positions explained the greatest amount of variance of any set of regression equations. Adjustments to the TCM tracks at 12-hour intervals resulted in predictions in the 1977-78 dependent test that nearly met the 7th Fleet forecast error goals. The selection of the velocity along the y-axis in the interval -12 to 00 hours as

the predictor explaining the most variance suggests strongly that systematic errors at or near initialization time were used advantageously to adjust TCM track forecasts. It is noteworthy to observe that TCM forecasts with all data samples used in these experiments incurred systematic errors (see Fig. 26).

It should be noted that the weak link in the regression adjustment scheme is the small sample size for derivation of the regression equations. With the exception of the 1975-76 equations, the regression coefficients have not been tested with an independent sample of storms. Application of the statistical equations in the future may not produce comparable results due to the relatively small number of cases used to derive the equations. Likewise some years have persistently anomalous storm tracks, as in the first sample (1975-76) treated here. It is expected that some increase in the stability of the regression equations could be achieved by increasing the number of TCM forecast cases used to derive the equations. This is especially true for the backward integration set.

In all of the experiments, the unmodified TCM forecasts were difficult to beat in the case of westward propagating storms. However, occasional improvement in velocity prediction was noted. The typhoons used in these tests had storm tracks in several general categories, such as westward, southeast-to-northwestward, northward, or recurving. Since the regression equations were derived from storm cases involving various combinations of these track types, it was felt that

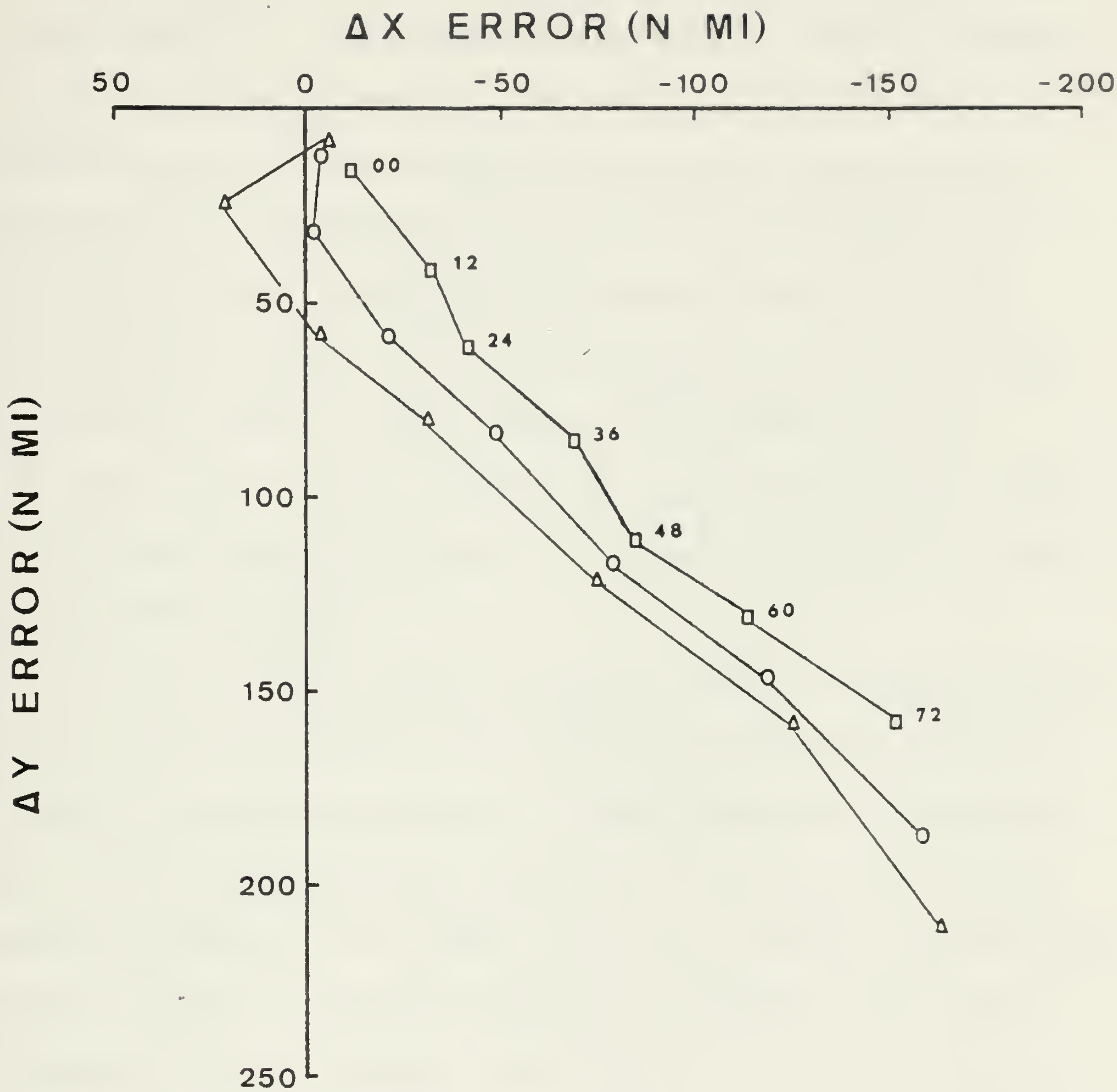


Figure 26. Mean errors of the TCM relative to the best track positions indicate systematic error. The ΔX versus the ΔY error is shown for the 1975-76 cases (□), the 1977-78 cases (Δ), and the combined cases for 1975-78 (O).

these widely varying tracks and subsequent errors contributed to failures of the regression equations to make proper track adjustments in some cases. A possible solution might be to vastly increase the TCM case sample size and then subdivide the cases into "regression analogs" according to the direction of typhoon propagation. The next step would be to derive a set of regression equations based on each subset of storm tracks. It could be expected that each subset of equations would have inherent adjustment biases towards the type of track from which they were derived. Any or all of these subsets of equations could be applied to each unmodified TCM forecast.

On the basis of the sample examined here, it appears that adjustment for recurvature was handled most effectively by the regression equations which included backward-integrated tracks. It is suggested that regression equations based on an expanded sample of TCM cases including backward integration should be derived to produce better adjustments and statistical equations with greater stability.

APPENDIX A: THE TROPICAL CYCLONE MODEL

A. THE FORECAST MODEL

The coarse-mesh version of the primitive equation model developed by Elsberry and Harrison (1971), Harrison (1973), Ley and Elsberry (1976), and Hodur and Burk (1978) was used as the basis for these experiments. The model is a coarse mesh (2^o), three-layer, dry model with one-way interactive boundaries on the north and south and cyclic east-west boundaries. The equations used in the model are:

$$\frac{\partial u}{\partial t} = -L(u) + fv - M\frac{\partial \phi}{\partial x} \qquad \text{(A-1)}$$

$$\frac{\partial v}{\partial t} = -L(v) - fu - M\frac{\partial \phi}{\partial y} \qquad \text{(A-2)}$$

$$\frac{\partial \theta}{\partial t} = -L(\theta) + \frac{Q}{\pi C_p} \qquad \text{(A-3)}$$

$$\frac{\partial \omega}{\partial p} = -M^2[\frac{\partial}{\partial x}\ (\frac{u}{M}) + \frac{\partial}{\partial y}\ (\frac{v}{M})] \qquad \text{(A-4)}$$

$$\frac{\partial \phi}{\partial p} = \theta\ C_p\ \frac{\partial \pi}{\partial p} \qquad \text{(A-5)}$$

$$\pi = (\frac{p}{1000})^{R/C_p}$$

$$\frac{\partial \phi_{1000}}{\partial t} = -V\cdot\nabla\phi_{1000} + \omega_{1000}(1/\rho_{1000}) \qquad \text{(A-6)}$$

where

$$L(S) = M^2[\frac{\partial}{\partial x}(\frac{uS}{M}) + \frac{\partial}{\partial y}(\frac{vS}{M})] + \frac{\partial}{\partial p}\ (\omega S)$$

L(S) represents the flux divergence of any scalar quantity S. The meteorological symbols used above can be found in the "List of Symbols".

A sufficient condition for the linear computational stability of the solution for two-dimensional equations governing simple wave motion is:

$$\frac{C\Delta t}{\Delta x} \leq .707 \qquad \text{(A-7)}$$

where

C $\equiv$ phase velocity of the fastest gravity wave

Δt $\equiv$ time increment

Δx $\equiv$ horizontal grid increment

Computational stability requires a maximum time step of 450 seconds for this model. Ley (1975) achieved an increase to 800 seconds by time averaging the pressure gradient term of the momentum equations. Shewchuk (1977) used a 600 second time step for testing his 1975 cases as the relocatable grid was extended northward where Δx is reduced. In the TCM version (Hodur and Burk, 1978) used for these experiments, the time step was 600 seconds unless the northern boundary exceeded 40°N, in which case the time step was 450 seconds.

The initial step was forward in time, while the leapfrog time differencing scheme was used in all subsequent iterations. Friction was neglected, and the consequent storm motion was primarily the result of advective processes and heating. A Bessel interpolator was used to locate the minimum wind at 1000 MB. Then latent heating was simulated by adding heat to a horizontal 7 x 7 grid centered on the minimum wind, which

was not necessarily on a grid point. Weighting of the heating function in the vertical was 0.3, 1.0, and 0.3 at 850, 550, and 250 MB respectively. In the horizontal, the effect of heating is smoothed out by a Cressman weighting function (Haltiner, 1971) and results in a less erratic storm track.

B. THE GRID

The forecasts are carried out on a uniform, coarse-mesh (2^o) Mercator grid true at 22.5^oN. The horizontal grid interval was 205.8 km. The domain consisted of 32 points east-west and 24 points north-south. The grid was oriented so that each storm was initially located southeast of the center of the grid. The vertical distribution of variables is shown in Fig. A-1. Although the variables are staggered in the vertical, staggering on the horizontal grid was not used in these experiments. The 850 mb winds were used to compute the advective terms at 1000 mb.

C. BOUNDARY CONDITIONS

Boundary conditions on the walls were after Hodur and Burk (1978). In the one-way interactive (OW) model, wind components normal to the boundaries are adjusted so there is no net divergence from the forecast domain. By integrating

$$\frac{\partial \psi}{\partial s} = V_n \qquad \text{(A-8)}$$

around the boundary, the corresponding ψ values are obtained (Hawkins and Rosenthal, 1965). Distance along the boundary is represented by s, while V_n is the velocity component normal

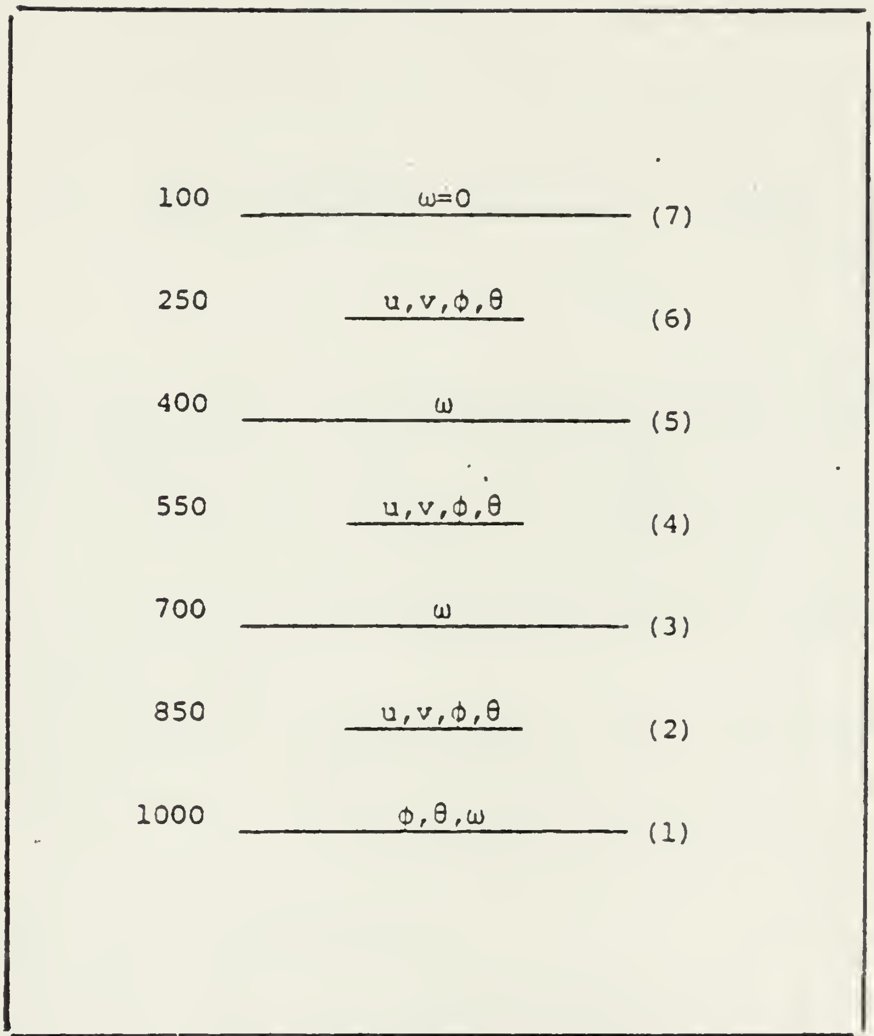


Fig. A-1. Vertical distribution of dependent variables and pressure levels for the three-dimensional model (after Harrison, 1973).

to the boundary with the positive direction being inward.

Date from outside the forecast grid must continuously be incorporated into the boundaries. This is accomplished as described by Perkey and Kreitzberg (1976), and following their notation, the prediction equation for a variable X becomes

$$X_n(i,j) = X_p(i,j) + W(i,j) \left.\frac{\partial X_m}{\partial t}\right|_{i,j} \Delta t + [1 - W(i,j)] \left.\frac{\partial X_{ls}}{\partial t}\right|_{i,j} \Delta t \tag{A-9}$$

where the subscripts n and p indicate the new and the previous value of X. The subscript m refers to the model tendency, while ls is the large-scale tendency. The weighting function used in this model was somewhat different from that given by Perkey and Kreitzberg (1976).

The following weighting function W(i,j) was constructed so that a minimum amount of noise was produced near the boundaries

0.0 on the boundaries

0.05 one grid row in from boundaries

0.25 two grid rows in from boundaries

0.45 three grid rows in from boundaries

0.65 four grid rows in from boundaries

0.85 five grid rows in from boundaries

1.00 on all other interior points

The forecast fields produced must be filtered near the boundaries. The filter used in this model is

$$\overline{F_j} = (1-\alpha)F_j + \left(\frac{\alpha}{2}\right)(F_{j+1} + F_{j-1}) \qquad \text{(A-10)}$$

where $\overline{F_j}$ is the filtered data at point j, F_j is the unfiltered data at point j, and α represents the smoothing parameter. The filter was applied every 40 minutes to the six rows and columns nearest the boundaries with $\alpha = 0.5$. This value of α yields a response function of 0 for a $2\Delta x$ wave. This filter is also applied over the entire grid to all the prognostic variables every three hours. In this manner the forecasts include large-scale tendencies from outside the forecast domain.

The vertical velocity at the upper boundary is equal to zero and is calculated at levels 5, 3, and 1, Fig. A-1, through downward integration of Eq. (A-5).

In an operational mode, the time dependent boundary conditions must be specified by a global forecast model. In these experiments, forecast fields were not available. Therefore, using a "perfect-prog" approach, analyzed fields taken every 12 hours were used to specify the boundary values.

D. INITIALIZATION

Analyzed fields obtained from FNWC are used as input data for the model. Initialization of the model is accomplished by calculating non-divergent winds from the stream function ψ.

The relative vorticity, the forcing function for the stream function, was obtained from the observed u and v components

$$\zeta = M^2 [\frac{\partial}{\partial x}(\frac{v}{M}) - \frac{\partial}{\partial y}(\frac{u}{M})] \qquad \text{(A-11)}$$

The normal component of the wind was adjusted so there is no net inflow or outflow in the domain. The stream function was found from the expression

$$\nabla^2 \psi = \zeta_r \qquad \text{(A-12)}$$

A direct solver (see Faulkner and Rosmond, 1976) rather than successive over-relaxation is used to efficiently solve the Poisson equations in the initialization process. The non-divergent wind components were then calculated through

$$u_\psi = -M \frac{\partial \psi}{\partial y} , \qquad v_\psi = M \frac{\partial \psi}{\partial x} \qquad \text{(A-13)}$$

An appropriate balance between the mass and motion fields is achieved through partial differentiation of Eq. (A-1) with respect to x and Eq. (A-2) with respect to y. Addition of these equations and assuming that the time rate of change of divergence and gradients of the map scale factor can be neglected leads to a Poisson equation

$$\nabla^2 \phi = - \frac{1}{M}(\frac{\partial}{\partial x}[L(u_\psi)] + \frac{\partial}{\partial y}[L(v_\psi)] + f[\frac{\partial v_\psi}{\partial x} - \frac{\partial u_\psi}{\partial y}] - u_\psi \frac{\partial f}{\partial y}) \qquad \text{(A-14)}$$

which can be solved using direct methods.

APPENDIX B. THE REGRESSION EQUATIONS

A. FORWARD INTEGRATION (1975-78 DATA)

The regression equations which follow were produced by SPSS using only predictors derived from forward integration of the TCM. The data sample consisted of 90 cases, or runs of the TCM.

1. TCM Integrated to 72 HR

```
                                                             %
                                                          VARIANCE
      REGRESSION EQUATIONS                                EXPLAINED

DXER12=-110.7609+ 1.5855(DX1224)+ 0.9154(DY2436)            52.4%
       - 13.9166(VX0024)+ 4.7875(XXLAT)
       -  0.3990(DY0012)- 0.2319(JULDAY)
       +  2.1836(VX6072)

DYER12=  33.3375+18.1010(VY1224)- 0.5674(DY0036)            60.8%
       +  4.4547(XXLAT) - 1.1054(DX3648)
       + 17.0027(VX3660)- 3.4188(VX6072)
       -  0.3610(DY6072)- 0.2033(JULDAY)

DXER24=-261.2548+ 0.0542(DX2436)+ 2.2207(DY2436)            51.5%
       + 11.2215(XXLAT) - 0.2442(DY4860)
       + 13.0592(VY1224)-19.3594(VX0012)
       - 20.6092(VY0036)- 0.4007(JULDAY)
       +245.7376(VX0036)+ 6.1574(VX6072)
       -289.1865(VX0048)+67.2472(VX3648)

DYER24= 371.6372+ 4.7059(XXLAT) -63.0716(VX6072)            54.9%
       +  6.3397(VY4872)-10.9032(VY0012)
       -  0.0693(DX1224)+18.3609(VX2436)
       -  1.4547(XXLON) - 4.9576(DX0048)
       +326.2109(VX0072)+ 1.5170(DY0024)
       - 41.8338(VY0072)-49.6258(VX4860)

DXER36=-344.7210+ 2.2548(DY2436)+ 0.7540(DX1224)            45.0%
       + 15.3565(XXLAT) +20.9332(VY1224)
       +  0.8946(DX6072)- 1.0326(DX3648)
       -  0.5088(JULDAY)-27.7637(VY0036)
       - 24.1194(VX0012)+27.4070(VX0036)

DYER36= 260.5690- 0.9549(DX0024)- 2.9255(DY2436)            55.2%
       -  1.3287(DX3648)- 0.5772(DY6072)
       - 15.5279(VX6072)+ 0.5606(DX0072)
       +  0.5077(DY0036)
```

```
DXER48=- 37.0420- 3.6915(VY2448)+ 2.9949(DX1236)      43.8%
       - 96.8508(VX0048)+16.3630(XXLAT)
       +  1.8046(DY1236)+ 8.7181(VX6072)
       +  1.9662(DX2436)- 2.4988(XXLON)

DYER48= 421.5829- 6.0309(VX0012)- 2.2291(DY2436)      55.5%
       - 20.5254(VX0072)- 0.5054(DY6072)

DXER60=  97.7600- 9.8039(VY2448)+16.2227(VX6072)      37.1%
       + 21.3398(XXLAT) + 6.1324(DX2436)
       - 59.0393(VX2448)+ 1.9753(DY1236)
       - 22.6283(VX0012)- 3.7782(XXLON)
       +  0.7277(DY6072)

DYER60= 426.2759-14.0207(VX0012)- 3.9702(DY2436)      61.5%
       -  0.1327(DX2448)-16.1361(VY4872)
       +  0.9047(DY0036)- 8.6688(VX6072)

DXER72= 332.5987+ 7.1491(DY2436)+20.2135(VX6072)      33.3%
       + 33.3952(XXLAT) - 5.1616(XXLON)
       -  9.6322(VY0012)- 1.0394(JULDAY)
       - 31.3262(VY4860)+ 3.7294(DX2436)
       - 41.6253(VX0048)

DYER72= 513.8518-19.1324(VX0012)-34.7630(VY4872)      67.5%
       - 11.1924(VX6072)- 3.0878(DY2436)
       + 32.4358(VY0024)
```

2. TCM Integrated to 60 HR

```
    REGRESSION EQUATIONS                               %
                                                  VARIANCE
                                                  EXPLAINED

DXER12=-107.0123+ 1.6448(DX1224)+ 1.1265(DY2436)      52.0%
       - 11.9798(VX0024)+ 4.3382(XXLAT)
       -  0.3577(DY0012)- 0.2152(JULDAY)
       -  0.2897(DY4860)

DYER12=  18.0425+15.8288(VY1224)- 0.5743(DY0036)      52.8%
       +  3.5755(XXLAT) - 0.9042(DX3648)
       +  8.4002(VX3660)

DXER24=-294.5950+ 0.5243(DX2436)+ 2.3803(DY2436)      47.7%
       + 10.6428(XXLAT) - 0.6973(DY4860)
       + 15.3517(VY1224)-18.4575(VX0012)
       - 16.4373(VY0036)- 0.3287(JULDAY)
       + 24.4865(VX0036)

DYER24= 315.0132+ 3.8023(XXLAT) - 1.2271(DX3648)      37.9%
       -  1.0044(DY2436)+ 7.6286(VX3660)
       -  0.9660(XXLON)
```

```
DXER36=-401.1984+ 2.3461(DY2436)+ 2.7807(DX1224)      41.1%
       + 14.1812(XXLAT) +25.5785(VY1224)
       - 29.8364(VY0060)+ 2.0807(DX2436)
       - 70.5401(VX0048)+ 0.9644(DX2448)
       -  0.3235(JULDAY)

DYER36= 323.7302- 0.3010(DX0024)- 2.2997(DY2436)      46.6%
       -  0.9578(DX3648)

DYER48=  11.4886-10.2403(VY2448)+ 2.9591(DX1236)      42.3%
       -127.1613(VX0048)+15.9606(XXLAT)
       +  2.0626(DY1236)+ 0.7195(DX0060)
       +  1.8145(DX2436)- 2.7430(XXLON)

DYER48= 417.1723- 6.5997(VX0012)- 2.4456(DY2436)      52.1%
       - 20.9459(VX0060)

DXER60= 121.4777+19.3487(VY2448)+65.1299(VX2436)      33.3%
       + 20.7381(XXLAT) + 2.2910(DY1236)
       - 23.5426(VX0012)-30.3043(VX2448)
       -  4.0537(XXLON) -24.8873(VY3660)

DYER60= 456.1107-12.6669(VX0012)- 3.8492(DY2436)      59.1%
       -  0.6316(DX2448)+23.5083(VY0036)
       -  0.7768(DY4860)
```

3. <u>TCM Integrated to 48 HR</u>

<u>REGRESSION EQUATIONS</u>	% VARIANCE EXPLAINED

```
DXER12=-104.2041+ 1.7146(DX1224)+ 0.8720(DY2436)      50.7%
       - 14.3293(VX0024)+ 3.6487(XXLAT)
       -  0.3320(DY0012)- 0.1562(JULDAY)

DYER12=  22.7200+18.7975(VY1224)- 0.5475(DY0036)      59.6%
       +  3.8778(XXLAT) - 0.0330(DX3648)
       + 15.9946(VX2436)-21.5329(VX0048)
       -  0.3737(DY3648)

DXER24=-313.4117+ 1.5624(DX2436)+ 1.0949(DY2436)      46.6%
       +  7.2252(XXLAT) +11.4632(DX1224)
       -518.1882(VX0048)+ 0.7746(DY1224)
       + 10.5539(DX2448)+ 9.8502(DX0012)

DYER24= 332.6320+ 4.7761(XXLAT) - 0.8977(DX3648)      45.4%
       -  1.6715(DY2436)- 0.5969(DY0048)
       + 29.4481(VY1236)- 1.0561(XXLON)
       -  6.7302(VX0012)+15.0708(VX2436)
       +  0.4376(DY0012)- 8.6575(VX1236)
```

DXER36=-449.5619+ 1.2046(DY2436)+14.0084(DX1224)   40.0%
+ 11.1369(XXLAT) + 16.8131(VY1224)
+ 1.9548(DX2436)-613.9317(VX0048)
+ 12.3598(DX2448)+ 11.3264(DX0012)

DYER36= 323.7302- 0.3010(DX0024)- 2.2997(DY2436)   46.6%
- 0.9578(DX3648)

DXER48=-512.1396-13.7846(VY2448)+ 3.2353(DX1236)   39.8%
- 91.2184(VX0048)+ 13.7796(XXLAT)
+ 1.8493(DY1236)+ 1.7217(DX2436)

DYER48= 416.0658- 6.3112(VX0012)- 1.8654(DY2436)   52.0%
- 0.7522(DX2448)- 0.4474(DY2448)

4. <u>TCM Integrated to 36 HR</u>

<u>REGRESSION EQUATIONS</u>	% VARIANCE <u>EXPLAINED</u>
DXER12=-104.2041+ 1.7146(DX1224)+ 0.8720(DY2436) - 14.3293(VX0024)+ 3.6487(XXLAT) - 0.3320(DY0012)- 0.1562(JULDAY)	50.7%
DYER12=- 5.4141+18.6196(VY1224)- 0.5781(DY0036) + 4.4260(XXLAT) - 0.2211(DX1224) + 12.1161(VX2436)- 0.3848(DX0036)	51.9%
DXER24=-290.9098+ 0.9820(DX2436)+ 1.8422(DY2436) + 7.4308(XXLAT) + 1.3908(DX1224) - 20.7300(VX0024)+ 12.9281(VY1224) - 14.9940(VY0036)	44.2%
DYER24= 331.9491+ 5.4103(XXLAT) - 0.5106(DY2436) - 0.6443(DX1224)- 4.7078(VY0012) - 1.1668(XXLON)	31.4%
DXER36=-431.3265+ 2.2294(DY2436)+ 2.2999(DX1224) + 11.7478(XXLAT) + 21.6634(VY1224) + 2.4042(DX2436)- 1.3375(DX0036) - 19.5387(VY0036)	37.8%
DYER36= 445.8439- 0.5419(DX0024)- 2.7621(DY2436) + 5.6707(XXLAT) + 19.5168(VY1236) - 1.4233(XXLON)	42.9%

B. FORWARD/BACKWARD INTEGRATION (1977-78 DATA)

The regression equations which follow were produced by SPSS using predictors derived from forward and backward integration of the TCM. The data sample consisted of 38 cases, or runs of theTCM in 1977 and 1978. Predictors in the equations are listed in order of decreasing significance.

1. <u>TCM Integrated to 72 HR, and -36 HR</u>

REGRESSION EQUATIONS	% VARIANCE EXPLAINED
DXER12= 133.7858- 1.1434(XXLAT) +49.0162(VX1236) - 0.8544(JULDAY)- 1.3384(DX0036) + 0.8434(DYM200)+ 0.2349(DXM6M2) + 8.1974(VYM6M4)- 1.9532(VX6072) + 0.2739(DY6072)	85.1%
DYER12=-323.6042-16.7634(VY0012)+11.7812(XXLAT) + 38.0056(VY0060)- 2.3118(VY0072) - 0.7205(DY2448)+ 21.8282(VX2436) - 34.3595(VX0036)+ 0.6223(JULDAY) - 0.3579(DXM6M4)+ 0.2499(DXM4M2)	86.5%
DXER24=1499.882+ 4.0720(VYM200) - 1.0176(DYM6M4) - 2.7329(JULDAY)+ 8.9808(VX1236) + 0.0302(DXM6M2)- 4.7254(XXLON) + 1.3513(DY2436)+ 19.7881(VXM400)	88.9%
DYER24= 132.9015+13.1693(XXLAT) - 0.4689(DY0024) - 12.0194(VX6072)- 1.2499(XXLON) + 10.8862(VX2436)- 0.3161(DXM6M4) + 12.5733(VY1224)- 0.5091(DY3648) + 0.5794(DX4872)- 12.1879(VX0036)	77.3%
DXER36=2313.2390+14.1025(VYM200)- 1.4677(DYM6M4) - 4.9703(JULDAY)+ 13.8301(VX1236) + 18.8607(VXM4M2)- 4.8841(XXLON) - 12.2852(XXLAT)	89.6%
DYER36= 208.2644+13.0715(XXLAT) - 2.1863(XXLON) - 2.3350(VX4872)+ 0.2046(VY2436) - 0.7827(DXM6M4)+ 12.3656(VYM6M4) + 0.9038(JULDAY)	74.9%

```
DXER48=3766.9010+ 3.9698(VYM200)- 7.5053(JULDAY)      92.4%
      +  2.9278(VX4872)-  27.2623(XXLAT)
      - 10.1248(VY0048)-  18.3859(VYM6M4)
      + 24.7589(VXM4M2)-   7.2417(XXLON)
      + 27.7765(VX1236)-   1.3987(DX3648)

DYER48= 587.8164- 1.2470(DXM6M2)-13.4294(VY2436)      81.0%
      -  5.9702(VX4872)+  91.4204(VYM424)
      -  4.3418(XXLON) +   0.2002(DX3648)
      +  8.8435(XXLAT) +   1.8326(JULDAY)
      +  2.0270(DXM4M2)-   1.4245(DYM212)
      + 20.3420(VYM6M4)-   1.3766(DYM200)

DXER60=4803.057 +19.0639(VYM200)-10.5486(JULDAY)      88.6%
      +  8.5565(VX4872)-  42.8314(XXLAT)
      - 46.1492(VY0024)-   6.9290(XXLON)
      +  2.3348(DXM4M2)-   1.6672(DYM6M4)

DYER60= 364.9735+ 0.6711(DXM600)+ 4.1587(JULDAY)      80.9%
      + 21.0652(XXLAT) +  75.9630(VY0024)
      +  2.0089(DYM6M2)-   7.1881(XXLON)
      -  2.7226(DXM6M4)-   2.0602(DYM212)

DXER72=3715.035 +87.8945(VYM200)- 6.6852(DYM6M4)      95.7%
      - 12.7603(JULDAY)- 115.0140(VY0048)
      + 42.7842(VXM6M2)-  39.1636(XXLAT)
      -  0.8422(DX6072)

DYER72=1214.7320-26.6951(VYM200)- 7.6189(XXLON)       93.2%
      -  2.7921(DXM6M4)+  62.8756(VYM6M4)
      + 38.9121(VY0024)+   3.1078(JULDAY)
      +  1.8961(DY3648)+  21.5763(VX3648)
      - 28.6336(VX0012)
```

2. TCM Integrated to 60 HR, and -36 HR

```
REGRESSION EQUATIONS                                   %
                                                  VARIANCE
                                                  EXPLAINED

DXER12= 167.5686- 1.1679(XXLAT) +42.0954(VX1236)      82.2%
      -  0.9556(JULDAY)-   1.1599(DX0036)
      +  0.8786(DYM200)+   0.2185(DXM6M2)
      -  5.6377(VYM6M4)

DYER12=-344.2685-14.9407(VY0012)+12.0804(XXLAT)       86.4%
      + 26.5455(VY0060)+   1.6737(DX2436)
      - 26.5420(VX0036)-   0.6601(DY3648)
      +  0.6473(JULDAY)-   0.3001(DXM6M4)
      +  4.9116(VXM200)
```

```
DXER24=1499.8820+ 4.0720(VYM200)- 1.0176(DYM6M4)     88.9%
       -  2.7329(JULDAY)+   8.9808(VX1236)
       +  0.0302(DXM6M2)-   4.7254(XXLON)
       +  1.3513(DY2436)+  19.7881(VXM400)

DYER24=- 56.4323+12.9000(XXLAT) - 0.3905(DY0024)     72.5%
       +  9.0748(VY4860)-   0.3743(DXM6M4)
       +  0.5430(JULDAY)-   0.9695(XXLON)

DXER36=2312.2390+14.1025(VYM200)- 1.4677(DYM6M4)     89.6%
       -  4.9703(JULDAY)+  13.8301(VX1236)
       + 18.8607(VXM4M2)-   4.8841(XXLON)
       - 12.2852(XXLAT)

DYER36= 518.1446+14.5509(XXLAT) - 37.9067(XXLON)     78.4%
       -  4.4077(VX4860)+   1.0088(JULDAY)
       +  1.2597(DYM6M2)-   1.6445(DXM6M4)
       + 19.1652(VXM600)+   9.2626(VY1224)
       - 13.8813(VYM400)

DXER48=3901.1060+ 0.1432(VYM200)- 7.1765(JULDAY)     92.2%
       - 26.0746(XXLAT) +  33.2885(VX1236)
       -  8.5896(XXLON) +   0.4893(DY2436)
       +  2.0444(DXM4M2)-   1.3676(DX3648)
       -  1.3292(DYM6M4)

DYER48=1228.8470- 3.0296(DXM6M2)- 9.9801(VY2436)     81.4%
       + 56.0325(VYM6M2)+   1.4210(JULDAY)
       + 50.1396(VY0024)-  47.0803(VYM212)
       -  5.8375(XXLON) +   2.5518(DXM4M2)
       + 43.1560(VXM600)-   7.6143(VX2436)

DXER60=5564.0920- 7.2041(VYM200)-10.5756(JULDAY)     90.5%
       - 55.6857(XXLAT) -1247.4050(VY0024)
       + 21.4406(VX4860)-   9.8929(XXLON)
      +1833.842 (VY0036)+   2.3392(DXM4M2)
       -620.6515(VY2436)+  26.8308(VY2448)

DYER60= 364.9736+ 0.6711(DXM600)+ 4.1587(JULDAY)     80.9%
       + 21.0652(XXLAT) +  75.9630(VY0024)
       +  2.0889(DYM6M2)-   7.1881(XXLON)
       -  2.7226(DXM6M4)-   2.0602(DYM212)
```

3. TCM Integrated to 48 HR, and -36 HR

REGRESSION EQUATIONS	% VARIANCE EXPLAINED
DXER12= 167.5686- 1.1678(XXLAT) +42.0954(VX1236) - 0.9556(JULDAY)- 1.1599(DX0036) + 0.8786(DYM200)+ 0.2184(DXM6M2) - 5.6377(VYM6M4)	82.2%
DYER12=-283.4282- 8.4050(VY0012)+ 9.2910(XXLAT) + 12.9974(VY1236)+ 1.2962(DX2436) - 17.6267(VX0036)+ 0.6355(JULDAY) + 5.6809(VYM6M4)- 0.2878(DXM6M4)	85.5%
DXER24=1499.8820+ 4.0720(VYM200)- 1.0176(DYM6M4) - 2.7329(JULDAY)+ 8.9308(VX1236) + 0.0302(DXM6M2)- 4.7254(XXLON) + 1.3513(DY2436)+19.7881(VXM400)	88.9%
DYER24= 129.5675+11.7946(XXLAT) - 0.4375(DY0024) + 10.8043(VY1236)- 0.5345(DXM6M4) + 7.9436(VYM6M4)- 1.4770(XXLON) + 0.5032(JULDAY)	75.9%
DXER36=2313.2390+14.1025(VYM200)- 1.4677(DYM6M4) - 4.9703(JULDAY)+13.8301(VX1236) + 18.8607(VXM4M2)- 4.8841(XXLON) - 12.2852(XXLAT)	89.6%
DYER36= 130.4497+13.4500(XXLAT) - 1.9319(XXLON) - 0.8659(DXM6M4)+13.7236(VYM6M4) + 0.9130(JULDAY)	74.5%
DXER48=3901.1060+ 0.1432(VYM200)- 7.1765(JULDAY) - 26.0746(XXLAT) +33.2885(VX1236) - 8.5896(XXLON) + 0.4893(DY2436) + 2.0444(DXM4M2)- 1.3676(DX3648) - 1.3292(DYM6M4)	92.2%
DYER48=1228.847 - 3.0296(DXM6M2)- 9.9801(VY2436) + 56.0325(VYM6M2)+ 1.4210(JULDAY) + 50.1396(VY0024)-47.0803(VYM212) - 5.8375(XXLON) + 2.5518(DXM4M2) + 43.1560(VXM600)- 7.6143(VX2436)	81.4%

4. TCM Integrated to 36 HR, and -36 HR

REGRESSION EQUATIONS	% VARIANCE EXPLAINED
DXER12= 167.5686- 1.1679(XXLAT) +42.0954(VX1236) - 0.9556(JULDAY)- 1.1599(DX0036) + 0.8786(DYM200)+ 0.2185(DXM6M2) - 5.6377(VYM6M4)	82.2%
DYER12=-283.4282- 8.4049(VY0012)+ 9.2910(XXLAT) + 12.9974(VY1236)+ 1.2962(DX2436) - 17.6267(VX0036)+ 0.6355(JULDAY) + 5.6809(VYM6M4)- 0.2878(DXM6M4)	85.5%
DXER24=1499.8820+ 4.0720(VYM200)- 1.0176(DYM6M4) - 2.7329(JULDAY)+ 8.9808(VX1236) + 0.0302(DXM6M2)- 4.7254(XXLON) + 1.3513(DY2436)+19.7881(VXM400)	88.9%
DYER24= 129.5675+11.7946(XXLAT) - 0.4375(DY0024) + 10.8043(VY1236)- 0.5345(DXM6M4) + 7.9436(VYM6M4)- 1.5770(XXLON) + 0.5032(JULDAY)	75.9%
DXER36=2313.2390+14.1025(VYM200)- 1.4677(DYM6M4) - 4.9703(JULDAY)+13.8301(VX1236) + 18.8607(VXM4M2)- 4.8341(XXLON) - 12.2852(XXLAT)	89.6%
DYER36= 130.4497+13.4500(XXLAT) - 1.9319(XXLON) - 0.8659(DXM6M4)+13.7236(VYM6M4) + 0.9130(JULDAY)	74.5%

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Thesis
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